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Research and Development Department

FINAL REPORT OF *RACE* PROJECT 2001: WTDM Pilot Installation

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Research and Development
Policy and Planning
THE BRITISH BROADCASTING CORPORATION

FINAL REPORT OF *RACE* PROJECT 2001: WTDM Pilot Installation

C.D. Mathers, (BBC, Ed.) *and* other Project Partners

Summary by BBC

The BBC has led two RACE-sponsored projects to develop the technology for a fibre-optic based video signal router. In the first project, R1036, prototype equipment was developed; a demonstration in 1992 showed that optical routeing was not only feasible, but could accommodate different signal formats such as serial digital 625-line and uncompressed EU-95 HDTV.

In a second RACE Project, R2001, which is the subject of this Report, the equipment was improved, production-engineered, provided with a user-friendly operational interface, and demonstrated in a working broadcast environment.

INTRODUCTION BY BBC

In the 1980s, the introduction of new television studio equipment led to new capabilities in programme production, and to new problems in the routeing of video signals around broadcast centres. First, the increasing requirement was for all sources to be available at all destinations, and second, the future need was to accommodate one or more new signal standards (serial digital component and later HDTV). One possible solution proposed at BBC R&D, was the combined use of time and wavelength division multiplexing (WTDM) over an optical fibre network; this inherently distributes all source signals to all destinations, and with suitable terminal equipment can carry any signal format.

To develop in prototype form the required optical and electronic technology, a consortium of European firms was set up. At just this time, the EU launched its first RACE initiative; after some negotiation the work was accepted as Project R1036, and carried out with EU support. R1036 was successfully completed in 1992, with a demonstration of a prototype routeing network distributing 270 Mbit/s digital component signals as well as audio and uncompressed EU-95 high-definition video signals at 1.152 Gbit/s. The Final Report of R1036 was published as BBC Research Department Report No. 1993/15.

R2001 was a further BBC-led collaborative project, again supported by the EU, to develop production-standard optical routeing equipment, and to demonstrate it in a working broadcast environment. The Project was successfully completed in September 1995 with a demonstration at NRK (Norwegian Broadcasting) in Oslo.

It is worth noting that the equipment (both optical and electronic) which was developed in this project has potential uses far beyond optical routeing, in the fields of digital video distribution, telecoms, and optical networks in general.

The document that follows is the Final Report of R2001 in exactly the form in which it was submitted to RACE Central Office; it therefore conforms to RACE rather than BBC format and style.

RACE 2001

REPORT ON COMMERCIAL EXPLOITATION

FINAL REPORT
1992 - 1995

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RACE PROJECT 2001

WTDM PILOT INSTALLATION

FINAL REPORT

COMPLETE REVIEW OF WORK FROM JANUARY 1992 TO DECEMBER 1995

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RACE PROJECT 2001

WTDM PILOT INSTALLATION

FINAL REPORT

COMPLETE REVIEW OF WORK FROM JANUARY 1992 TO DECEMBER 1995

1 SUMMARY

This Project has built on the work of the RACE I Programme, especially Project R1036, *WTDM* (wavelength and time division multiplexing) by specifying, installing, testing and demonstrating an optical broadband Customer Premises Network (CPN) for a real application in a working environment. Work has included the development of optical networks and the optical and high-speed electronic subsystems and components needed for such an installation.

At the outset a target site had been identified for a pilot installation: namely, the BBC's Welsh Regional Centre at Cardiff. The main achievement of the first full year's work was to produce a costed specification for this installation; in support of this aim, work started on component design and on research into techniques that would be used in future optical CPNs. During the second year the costed specification was considered by BBC Wales. They agreed that it was technically acceptable and offered operational advantages, but the estimated costs were beyond the resources allocated for refurbishment of the Cardiff communications centre; it was therefore not possible to proceed with an optical installation there.

With the co-operation of all Partners, the Project was redirected towards an installation based on flexible optical interface units (OIUs) which are well adapted to the needs of broadcasters. At the same time, a new site for the pilot installation was looked for. In November 1993, agreement was reached between Norwegian Broadcasting Corporation (NRK) and GEC-Marconi Defence Systems that a phased pilot installation of the WTDM routeing technology would be undertaken at NRK in Oslo during 1994-5.

The first step in this work was to define and agree the requirements of the installation phases at NRK. Initially conceived as two phases, I (initial fibre fabric carrying 270 Mbit/s digital video) and II (2.5 Gbit/s wavelength-multiplexed router), the networks were combined into a single pilot installation which included both direct optical links and optical signal routeing based on wavelength and time division multiplexing (WTDM). Detailed planning was undertaken to ensure that the pilot would meet the requirements of NRK; in particular, a requirements document was produced, followed by an installation proposal with detailed layouts. Practical considerations such as equipment layout in racks to give optimum thermal performance were taken into account. A modular system was developed, and new backplanes designed, along with improved designs of direct link equipment. The control system was developed and interfaces written for all WTDM components. The concept of the pilot had already been thoroughly validated by the demonstration held in March 1995 at RAI Research Centre in Turin, and was proved beyond doubt to the public at NRK in Oslo during and after September 1995.

Most of the work on component development was completed during the first three years of the Project.

Notable achievements were:

- DFB lasers can now be produced to given wavelength with high yield, with all control, monitoring and alarm circuitry laid out within the standard Project module. They offer problem-free integration with the rest of the system hardware. Improvements to DFB laser manufacture, packaging, driving and optical isolation techniques have confirmed the capability to write gratings at the specified WDM wavelengths and to achieve very high performance using commercially available ancillary devices.
- Silica-on-silicon arrayed-waveguide, single-mode to single-mode, 1 × 8 wavelength demultiplexers have been produced, integrated with V-grooves (for the passive alignment of input and output fibres). The target specification of 8 channels, 4 nm

channel separation, -20 dB crosstalk between channels and a fibre-to-fibre insertion loss of less than 6 dB has been well exceeded.

- Bulk-optic wavelength demultiplexers have been developed with more than 40 channels at spacings down to 0.5 nm and with losses less than 1.5dB and crosstalk as low as -60 dB. To our knowledge, this performance has never before been equalled.
- Four high-speed ASICs for the electrical multiplex and demultiplex have been produced, and the complete systems with their Intel Bitbus control have been fully tested.
- Progress in lithium niobate optical switching devices has included tuneable filters working down to 0.5 nm channel spacing and devices with flat passbands suitable for concatenation. An optical switch, fully packaged, was demonstrated at Oslo.
- A 12×12 STM-16 switching matrix board with two fully-equipped STM-16 clock-recovery boards (four STM-16 channels on each board), and two STM-16 optical receiver boards were delivered for the Oslo demonstrations.
- The video interfaces (coder and decoder) have been completely tested and integrated in their 2U racks, and were demonstrated at Oslo.
- Production engineering of the low and medium bitrate user interface boards has been completed. Four production versions were installed at NRK in Oslo.
- Production engineering of a copper-zinc injection-moulded single-mode optical backplane connector has been completed, as well as field testing of the connector and its related tools.

2 RELATIONSHIP WITH THE RACE PROGRAMME

The publication *A strategic audit of the development of advanced communications in Europe (April 1993)* reinforced the position of R2001 within and beyond the RACE Programme:

> " In the broadband context, technologies that likely merit continued or increased support include all optical networks .... [p. 12];
>
> The main technology breakthroughs required for optical communications to be deployed extensively in the users networks are the development of monolithically integrated optical subsystems, free packaging techniques for optical components, and mass-manufacturing techniques. [p. 13];
>
> Wavelength multiplexing will best contribute to the deployment of almost fully photonic networks .... These technologies [WDM and coherent] are the clear long-term target, but require development of cheap and mass-manufactured integrated optical circuits. [p. 14]
>
> Priority in research at EC level should be on multi-wavelength networks, including network survivability, wavelength control, optical routing, and development of monolithically integrated photonic subsystems, including their manufacturing techniques. [p. 14] "

R2001 has drawn on and further developed the following technologies developed in RACE I projects: R1008 (silica-on-silicon technology), R1027 (DFB -distributed feedback- laser wafers), R1031 (MQW -multiple quantum well- lasers), R1033 (optical switching), R1036 (wavelength and time multiplexing), R1081 (signal interfaces to SDH), R1089 (optical connectors, radiative star optical coupler), R1092 (reliability analysis and databases).

In RACE II R2001 had its closest ties with R2065 (COBRA) which built on the success of the RACE I project R1010. Coherent technology is seen as one logical next step to provide a broadband CPN that could be used with large numbers of HDTV signals. The initial intention was that R2001 would provide an application in which the coherent technology being developed by R2065 could be demonstrated. This was expanded into three combined demonstrations; one at BBC R&D Open Days in September 1994 (COBRA's public début), one at RAI (Turin) in March 1995, and one at the pilot installation (NRK, Oslo) in September 1995 (now all successfully completed).

Links were also developed with R2018 (GAIN), R2028 (MWTN), and R2070 (MUNDI). R2070 had interests in WDM techniques and devices.

Contact was maintained with R2028, multi-wavelength transport network: discussions were held and Annual Review Reports were exchanged between R2001 and R2028. R2001 also worked with R2039 (ATM optical switching) where a common interest in wavelength multiplexing, optical switching and developing optical systems models created synergy.

Techno-economic modelling tools from R2085 (INTERACT) were assessed for their applicability to the modular, evolutionary R2001 system, and were used in the design of the final pilot installation.

The Project's optical wavelength demultiplexers were used in other RACE Projects, and are being used in the ACTS Project WOTAN.

Demonstrations in public at exhibitions such as IBC, ITS and ECOC enhanced the perception of the RACE programme among Community institutions and the technical and broadcasting communities in general.

3 OBJECTIVES

3.1 General objectives of the project

The aim at the outset of this Project was to build on the work of R1036 and other RACE I projects by specifying an optical broadband Customer Premises Network (CPN) for a real application and, if the specification and costs were acceptable to the user, to install the network. At the outset a target site had been identified for a pilot installation: the BBC's Welsh Regional Centre at Cardiff, selected because the communications centre at Cardiff was due for refurbishment during the timescale of RACE II.

Work in the first year showed that Cardiff was an excellent site for an application study, and a great deal was learnt in the preparation of a costed specification in the first year of the Project. Whilst the proposal was technically acceptable and offered operational advantages, the estimated costs (for an extremely large and comprehensive installation) were beyond the resources available at that time. During the second year the objectives of the Project were revised as a result of the experience in Cardiff in order to address better the commercialisation issues raised. Agreement was reached to install a very much smaller pilot routeing system in the premises of NRK (Norwegian Broadcasting Corporation) in Oslo. Work was continued on components that offered the possibility of cost savings in future systems.

A number of RACE I projects have produced demonstrators that have verified technological aspects of the broadband CPN. However, the components developed in RACE I are generally laboratory prototypes. Work in this Project has improved these components to the point where a sufficient number of proven units (with other applications in IBCN) have been fabricated for a pilot installation. The demonstration networks are based on the techniques demonstrated by R1036 in which signals from all sources are combined at local routeing centres (LRCs) by wavelength and time division multiplexing (WTDM). The combined signal is distributed to all destinations, where the signals required are demultiplexed. Fig. 1 shows the system architecture which was first demonstrated by R1036 and which forms the basis of R2001. Units needed for such a system are optical connectors, electrical multiplexers and

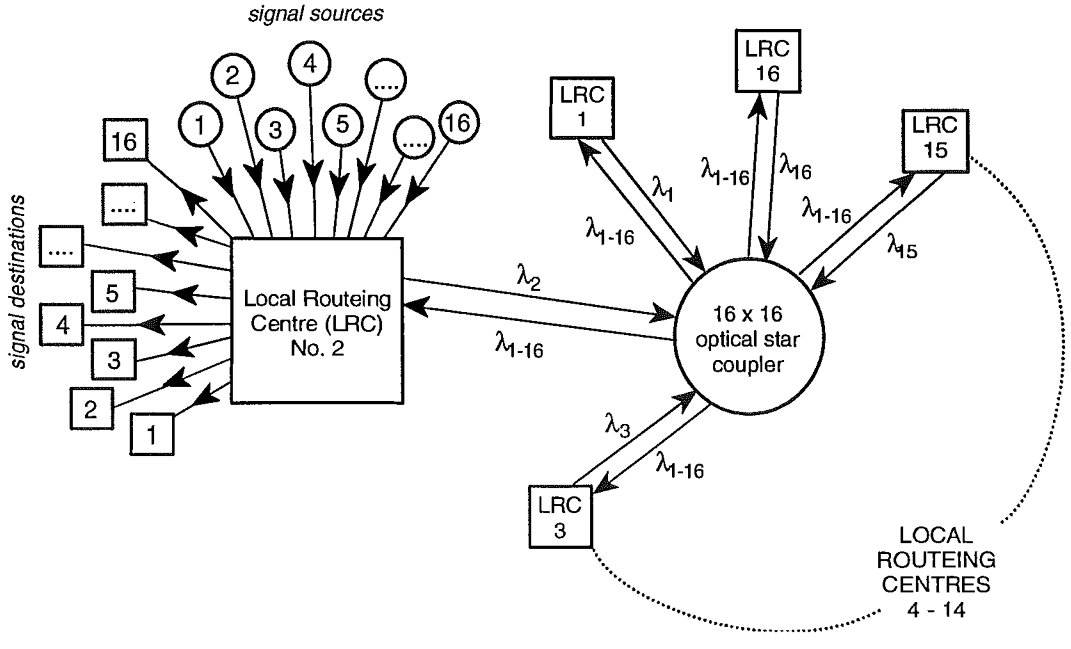

Fig. 1 - Basic architecture of WTDM installation

demultiplexers, laser transmitters at controlled wavelengths, optical star couplers, optical demultiplexers, optical receivers, control system, signal interfaces, and the signal mapping for a public network interface. All of these are now complete.

In conformance with the aims of RACE II to "maintain a high level of technological work", advanced techniques, such as optical switching and coherent detection have been developed, in this Project and in collaboration with other RACE II Projects, to augment or extend the capabilities of the CPN.

It is seen that successful exploitation of a technology depends initially on the endorsement of a well defined, technologically responsive user group; for the work of R2001, broadcasters form such a group. Thus the work of this Project should help to ensure that broadband CPNs become available to broadcasters and others who will need them to exploit the potential of Integrated Broadband Communications.

3.2 Specific objectives

The objectives as set out at the beginning of the Project are listed below. Each formed a clearly defined workpackage and was given a 'WP' number for administrative purposes; these numbers have been retained to allow cross-reference with the next section, **4**, which describes the achievements in each workpackage during the Project. (Two workpackages, WP4.1 and WP4.2, were for internal administration only and are not described in this report.)

WP1.1

Monitoring

To monitor developments in component technology within this and other RACE projects as well as elsewhere, so that component specifications can be updated for future systems. To maintain close contact with other RACE projects and other organisations (e.g. BELLCORE).

Specification

To write a specification for the WTDM pilot installation. This entails liaison with the customer to define the precise requirements, and with the Partners who are supplying the equipment to ensure that these requirements are fulfilled in the most effective and economical way possible.

WP1.2

Test bed/safety

To develop a test bed for testing subassemblies and their interfaces to ensure complete system interoperability. To monitor optical safety standards as they develop.

WP1.3

Installation

To install and populate the pilot router, incorporating modules supplied by Project Partners. To commission and test the installed router.

To follow up opportunities for WTDM trials in other areas.

WP1.4

Maintenance tools

To provide a monitoring station for complete maintenance. To provide on-site test facilities sufficient to isolate faults at the sub-assembly level.

To provide a portable PC-controlled tuneable wavelength selector with 0.2 nm resolution, full data processing and logging, 2.5 Gbit/s signal bandwidth, and a mercury wavelength reference at 1529.582 nm.

WP1.5

Network architecture

To examine the R1036 network (Fig. 1) and to develop new architectures offering some optical path redundancy. To ensure a degree of future-proofing of the installation through capacity and control/management studies. To determine, through costed trade-off studies, the design margins and enhancements to support a range of future requirements.

WP2.0

Optical interconnection

To produce a low-cost backplane EC monomode connector using copper-zinc alloy injection moulding techniques, and complete its qualification tests in order to obtain a commercially available product. To field test the connector and its installation and maintenance tools.

WP2.1

High speed electronics

To production-engineer and manufacture six ASICs; three for electrical multiplex, demultiplex and switching, three for interfacing between STM-1 and STM-16 data formats.

To design the multiplex and demultiplex boards for interfacing between STM-1 and STM-16.

To fabricate, tune and test a 2.5 Gbit/s 12×12 switching board and the two associated STM-16 clock recovery boards. for implementation in the pilot installation. To validate the performance of the switching matrix associated with the STM-16 optical receiver.

WP2.2

Optical transmitters

To optimise the manufacturing processes for producing distributed-feedback (DFB) lasers at required wavelengths, and to package these with optical isolators, thermal control, and monitoring circuitry.

WP 2.3

Optical demultiplexer (integrated)

To develop silica-on-silicon arrayed waveguide wavelength demultiplexer devices. To deliver a prototype fibre pigtailed and packaged single-mode to single-mode 1×8 WDM device with 4 nm channel separation for evaluation in the system test bed and the pilot installation. To environmentally test devices. To achieve a target specification of better than -20 dB inter-channel crosstalk and maximum 6 dB fibre-to-fibre insertion loss. To fabricate further WDM chips with new designs with the aim of improving interchannel crosstalk.

WP2.4

Optical demultiplexer (bulk)

To develop a 16 to 32-channel demultiplexer with channel spacings down to 1 nm and loss less than 2 dB, single-mode to single-mode, crosstalk less than -20 dB, channel peak less than 10% of channel spacing; to operate at ambient temperatures between +10 and +40°C.

WP2.5

Optical receivers

Based on the knowledge gained in R1036, to design an economic and easily manufacturable 2.5 Gbit/s optical receiver with clock recovery and sensitivity better than -30 dBm.

To design a silicon ASIC for 2.5 Gbit/s clock recovery. To fabricate, tune, test and qualify two sets of two-channel 2.5 Gbit/s boards.

WP2.6

Control

To design and implement a reliable, cost-effective control interface for a WTDM network, flexible enough to cope with anything from a low-cost entry-level point to point system to a full non-blocking broadcast router. To investigate the possibility of a distributed implementation of the network control system. To specify a protocol for communication between the control system and the network nodes.

WP2.8

User interface

To define and specify the strategy and components for routeing the user's video, audio and ancillary signals.

WP3.3

Optical switch

To establish a working electro-optic tuneable filter (EOTF) switch module for demonstration in the pilot installation. The device will be temperature controlled and will interface with the network control system.

To develop new EOTF designs. New lithium niobate to be produced to address process and manufacturing information for improving the performance of further developments.

4 ACHIEVEMENTS

The work done in the course of the Project, and its technological achievements, are described under the workpackage headings used in the previous section.

WP1.1

Monitoring

Throughout the Project, developments in technology were monitored through a presence at Concertation Meetings and other fora. Discussions were undertaken with other broadcasters to monitor their requirements for optical routeing equipment.

Specification

User requirements

During the first year, the requirements of the BBC studio centre in Cardiff were analysed and agreed by the users and the Partners. During the second year, a costed specification was submitted by Partner GEC-Marconi.

Early in the third year, when BBC Wales for economic reasons decided not to proceed with the installation, the Partners decided to repackage the equipment in a flexible modular form to make it easily installable for a wide range of applications.

Later in the third year, agreement was reached with Norwegian Broadcasting (NRK) in Oslo to install and demonstrate a pilot WTDM system. The specification, design and installation of the network were completed during the fourth year, and the installation was demonstrated in September of that year (1995).

Optical aspects

During the first year, a list of optical constraints was prepared by discussion between optical Partners, and agreed target specifications were prepared, based on standards where available, and otherwise on the performance of actual devices. These constraints were used in constructing optical power budgets for the comparison of proposed optical network architectures, described later.

Component supply

Information was continually gathered from all Partners, initially from a questionnaire, to define the form and fit of the components or modules that they were intending to supply to the installation. The questionnaire performed the dual purpose of guiding suppliers towards the features that they needed to define before a complete system costing could be prepared, and in providing a consultation document which GEC-Marconi could use to ensure that supplied components or modules would interface without any hidden gaps.

WP1.2

Test bed

The test bed work was initially divided into two parts: the specification of the form of the test bed, and the provisioning of the equipment. The form was defined as a 'skeleton' which allowed the functionality but not necessarily the scale of a pilot network to be tested.

The skeleton comprised a laser driver and transmitter, an optical star, a tuneable optical filter, an optical receiver and a clock recovery circuit.

The major items of test equipment that were added were a bit error rate tester, a tuneable laser source, a high-speed sampling oscilloscope with an optical interface, an optical power meter and a programmable optical attenuator.

All of these components were capable of operation at 3 Gbit/s. The bus used to control them was of the HPIB type.

The test bed equipment has been used extensively for the measurement and integration of equipment for pilot installation. Long-term error-rate monitoring tests have been performed, and optical characterisation of components undertaken. A harness completely compatible with the modular design of the pilot installation components has been developed and extensively used for test purposes. A general view of the test bed appears in Fig. 2, and Fig. 3 shows the complete system under

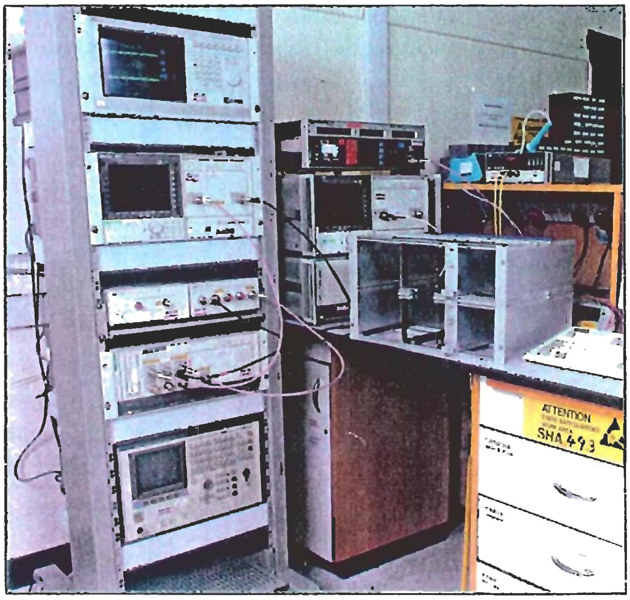

Fig. 2 - Test bed: general view

computer control.

Equipment from the test bed has also been used, not only by other Partners for characterisation of their own equipment, but also in system demonstrations, especially at BBC R&D and at RAI Research Centre.

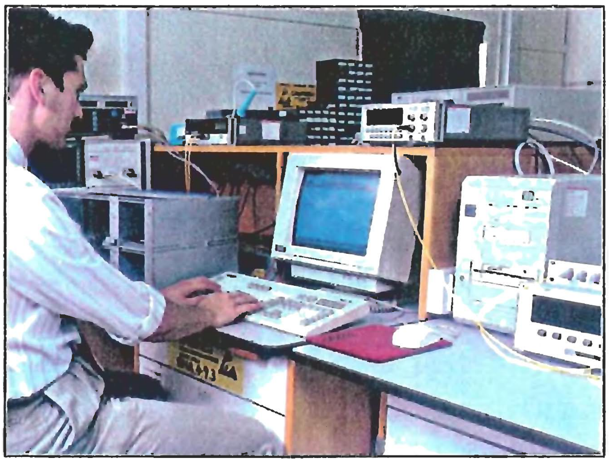

Fig. 3 - Test bed: computer control

WP1.3

Installation

The pilot installation represented an exciting advance in optical networking, and was, without doubt, the largest capacity network installed in user premises at that point in time. The performance and presentation of this installation have ensured that the technology has been seen and appreciated by many influential players in the broadcasting community.

The installation showed the elements of the WTDM system working between four operational areas. The equipment in the central technical area contained links which operated at the direct rate of 270Mb/s and WTDM links operating at 2.5Gb/s. All system wavelengths and the data streams carried on them were available via the wavelength demultiplexer in this area. Electronic switching allowed sources to be selected. A touch screen control was located in this area and could be used to control the routeing network. The tape and film area was connected to the system over 270Mb/s direct links and did not contribute to the WTDM multiplex, although all signals were controlled by the control system, and the hardware conformed to the same modular layout used in all other areas. Sources in Studio 5 and the programme building contributed to both the direct interconnection layer and the WTDM stream. Fully modular wavelength demultiplexing and electrical demultiplexing components permitted sources from anywhere on the network to be selected and routed within these two areas using the control system. A detailed schematic of the pilot installation is shown in Fig. 4.

The majority of the equipment installed to perform routeing operations was designed to show the versatility of the modular system. There were only a limited number of SDH components available for the pilot, and it was necessary to show these working as part of a larger fibre-optic installation. The components which were available from partners were disproportionate in their availability, in that there were 14 laser wavelengths in the system, giving a maximum capacity of 35Gb/s, but only four 2.5Gb/s optical receivers. The occupancy of the SDH containers was consequently very low, and the pilot showed the capability for high speed rather than an actual very high speed system in operation.

During the week 7th to 14th September 1995 a series of presentations and demonstrations were held in order to present the pilot installation to as large an audience as possible. Among many significant visitors were the R2001 and R2065 Project Officers from RACE Central Office, the EBU (European Broadcasting Union) steering committee and BBC senior management. Each presentation started with a presentation of NRK by the Technical Director of NRK or his representative. A presentation by the RACE 2001 project manager from the BBC was then given in which the project history was described, and the components which comprised the pilot installation were shown. There followed a presentation of the pilot installation by GEC-Marconi. This presentation showed the reasons for the adoption of a layered approach (direct links and WTDM "global" links) and the way in which the adoption of a modular approach has benefited the installation. The control system was described, and the presentation concluded with mention of the commercialisation state of the equipment. This presentation was followed by a representative of the COBRA project (RACE 2065, coherent optical connection) showing the potential advantages of coherent optical technology (bandwidth and tunability) and describing the HDTV demonstration at NRK.

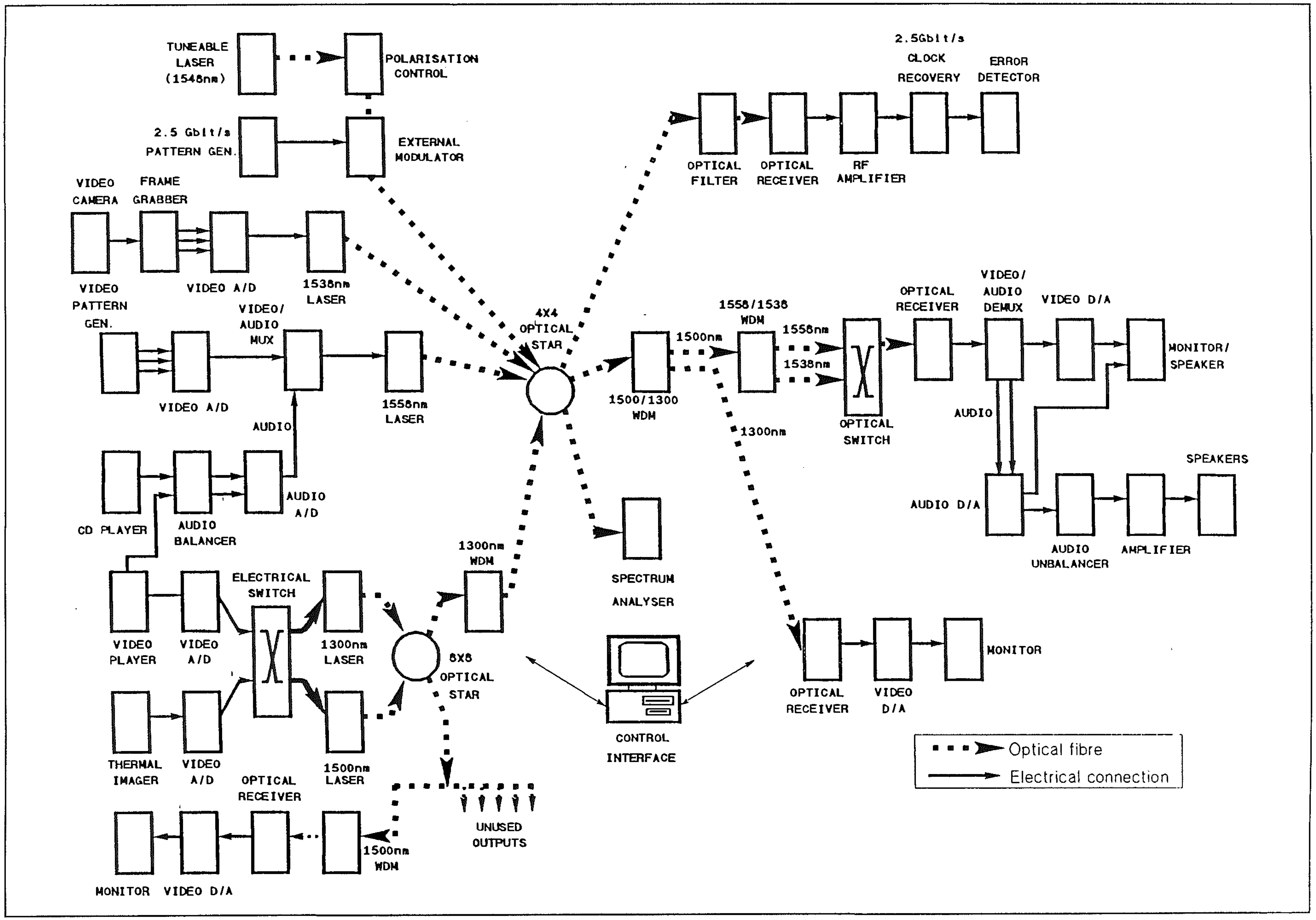

Fig. 4 - Schematic of the pilot

The presentations were followed by demonstrations of the working equipment in the CTA (central technical area) where the test equipment and COBRA receivers were located. The control system and the installed transmitter receivers were shown. The party then visited two other equipment locations, in Studio 5 and the programme building, to see the equipment mounted in standard studio racking. These latter areas were important to view, since they showed that the WTDM routeing equipment is produced to a build standard compatible with other studio equipment, and that it was installed in a professional manner.

WP1.4

Maintenance tools

Thomson CSF/LER and Jobin-Yvon worked together to define a tuneable wavelength demultiplexer associated with an optical receiver and a clock recovery function able to work in a harsh environment for maintenance and monitoring facilities. This module was to include, by means of an optical coupler, a power meter, which would be very useful to detect laser failure or even bad optical connections. After consideration of several configurations, a mechanically scanned Stimax was implemented, controlled by a PC with dedicated software. The complete instrument, which is fully portable, is shown in Fig. 5; the box measures 400×580×380 mm.

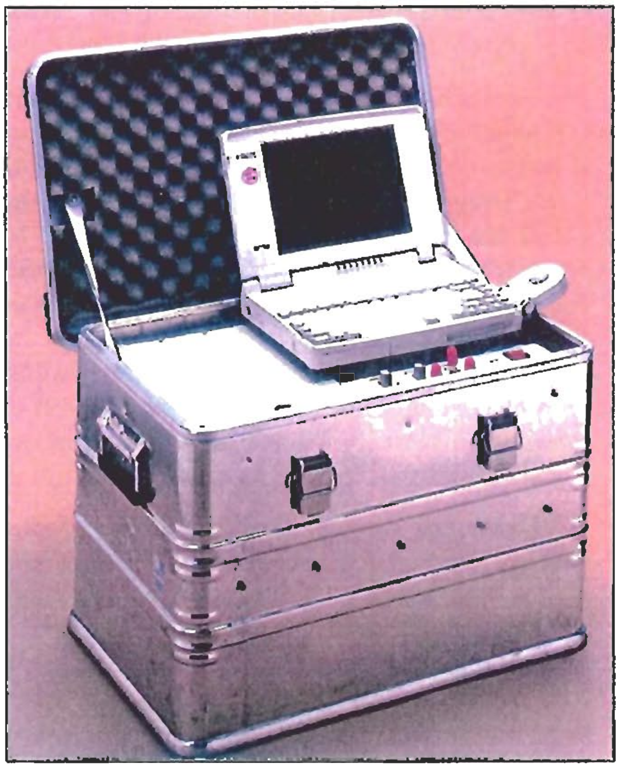

Fig.5 - Tuneable wavelength analyser

Resolution is 0.2 nm; an inbuilt standard wavelength source is provided. The wavelength stability of the scan is 0.01 nm/°C without thermal control, or better than 0.0001 nm/°C between -20 and +60°C with Peltier stabilisation. Wavelength dependence on polarisation is zero; loss dependence on polarisation is about 3% over the R2001 wavelength range (1530 - 1560 nm).

The software allows spectra to be plotted, recorded, and mathematically manipulated.

WP1.5

Network architecture studies

A number of activities have been performed under this work package, all of which are intended to improve the understanding of WTDM optical network routeing, and therefore to permit improved designs to be implemented at lower cost. The scope of the work was extended to review the applicability of modular networks to the requirements of other broadcasters and users, and reviews of commercial issues have been carried out.

a) Globally interconnected multiple star (GIMS) networks like the one shown in Fig. 6 have been analysed in detail, and it has been found that such networks can be designed within a fixed set to achieve various levels of redundancy and expandability.

b) A cost reduction exercise was carried out in order to ensure the commercial viability of the WTDM router. A pro-forma was produced

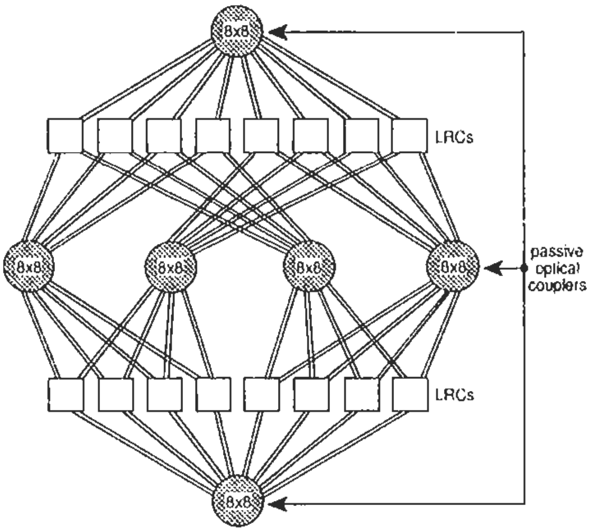

Fig.6 - Globally interconnected multiple star network

and circulated to other Partners in order to assess the potential for reducing the cost of key components, and hence the cost of the overall system.

c) An analysis of failure modes and effects was carried out for the proposed system architecture. This analysed the various ways in which equipment may fail and the effects of these failures on the next highest level in the system, propagating up to system level. Block diagrams have been constructed to enable the availability, reliability and maintainability of the system to be assessed.

d) Discussions were held with a number of broadcasters, ranging from major national companies to small post-production houses, in an attempt to clarify the extent of the potential market for fibre-based signal routeing. It is clear that many people in the industry accept the ultimate inevitability of fibre-optic based routeing, although there is of course also strong conservatism. The cost of such a system is also paramount: broadcasters are not prepared to spend more for a fibre-based router than they would for conventional technology unless the fibre technology offers operational advantages or long-term cost savings. The cost reduction exercise and a modular approach to the system design were therefore seen as critical to the future commercial viability of WTDM routeing.

It has become clear during the course of this project that there are a wide range of architectural implementations which can be applied in order to meet a given user requirement. There is a compromise to be made between cost and functionality, and in order to understand this compromise and achieve the best result the network proposed must be tailored to each individual requirement. It was for this reason that a highly modular set of components was proposed and implemented in this project, with the aim of providing a number of building blocks which could be utilised as appropriate to give the required functionality, but which could also be reconfigured as and when necessary in order to meet changing situations or the demand for an expanded network. It was found that in order to offer a low-cost entry point to fibre optic CPNs it was necessary to propose an architecture in which some interconnections between functional areas are made using direct point-to-point links and other connections are made via a distributive star carrying WDM and WTDM signal paths.

There are a number of ways in which a feasible architecture can be designed using the direct connection and global connection options. A dedicated link is only ever made between two discrete points. The connection can therefore take the most cost effective form and is independent of any other links in the network (the equivalent in the broadcast situation of a tie-line). A routeable link is one which is only ever made between two points, but which may be changed in normal operation to a different source or destination. In general a routeable link only affects a path from a given source which may be re-routed to a different destination, or a destination which may require to be re-routed to a different source. This type of link is not independent of other connections through the network since different physical paths may be used in order to effect the new links. A multi-cast link is one which connects a single source to a number of destinations. The connections made could be fixed as in the dedicated link, or could be reconfigurable as in the routeable link. Any link or links can be made, broken or re-routed without interrupting or otherwise affecting any other links. A broadcast link is a special case of a multi-cast link. In this instance a single source is connected to every destination. There is therefore no reconfiguration necessary, although redundant routes may be provided through the physical network.

The architectural approach proposed and used in RACE2001 WTDM permits each of these types of links to be set up, and allows all types of links to be integrated into a single network. It also allows the types of links to be interchanged, by physical or logical reconfiguration of the system. The type and rate of data to be transferred across the network will also affect the choice of components, and another strength of the modular system adopted is that the nature of a link can be changed very easily by the use of a different module within the physical structure.

Given this extreme flexibility, it becomes a very complex task to design the best network to meet a given set of requirements. In order to start this process, a model of such networks has been generated which can be used to evaluate all of the components necessary to meet a particular customer requirement, and to adjust the relative numbers of different components and link types in order to optimise the cost of such a network.

The conclusions of this analysis are that, at current component prices, there is too great a cost step to encourage a user to use WTDM in preference to direct fibre links at present, but that, given some believable targeted reductions in the prices of some components the use of WTDM for increasing network capacity and for providing routeing facilities would be capable of economic justification.

WP2.0

Optical interconnection

A new backplane EC connector has been developed which comprises:

- an EC-BPO adaptor mounted in a DIN 41612 backplane receptacle
- an optical contact mounted in a DIN 41612 plug
- a standard EC connector plug
- guides for pre-alignment

A total of 52 connectors have passed the following qualification test file:

- insertion loss
- return loss
- vibration (sinusoidal, 10 g, 30 min/axis, 3 axes
- temperature change (-25 to +70°C)
- Mechanical endurance (500 matings and unmatings)

The results on the main optical characteristics were:

- **mean insertion loss** 0.42 dB (0.50 dB required)
- **max. insertion loss** 0.78 dB (1.0 dB required)
  ...standard deviation 0.15 dB
- **coupled return loss** >60 dB (≥60 B required)
- uncoupled return loss >50 dB

Tooling for installation and maintenance are available.

To reduce costs, a copper-zinc alloy injection moulding has been designed. The original object of designing a modular piece part which could be used with two standards - both DIN 41612 and 2 mm metric - was abandoned due to difficulties in obtaining the high-precision moulding.

Connectors were supplied for the Pilot Installation and were judged satisfactory by the users. The comments made by the users were taken into account in the final version of the connector, which is shown in Fig. 7, and which is now a commercial product.

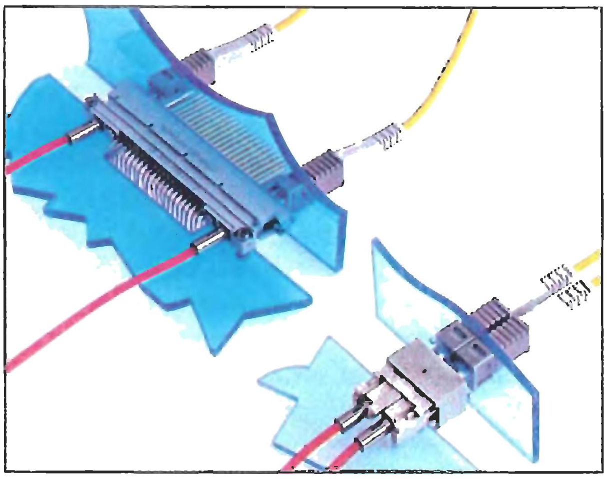

Fig. 7 - Optical backplane connector

WP2.1

High speed electronics

Based on the results of the first-year study into the transmission of high bit-rate signals within a large-scale network, the architecture for the multiplex and demultiplex subsystems was completed during the second year. This work built on research carried out in R1036. However, a number of major design changes were required for the pilot installation. These included clock recovery, and the ability to frequency- and phase-adapt the incoming data streams for synchronisation to the multiplexed frequency source. It was also important to incorporate bit-error detection at each processing stage in the transmission system to facilitate fast detection and protection thereby minimising the down time. These functions conform to the CCITT Recommendations G.707, 708, 709 and G.782, 783, 784.

The architecture requires four 155 Mbit/s ASICs, a bit interleaver and retimer (BIRT), a shuffler-scrambler (SHUMBLER), an STM-1 ADAPTER, and a clock recovery circuit. During the second year full specifications for the integrated circuits were completed. The circuit designs and chip layouts of the BIRT, SHUMBLER, and STM-1 ADAPTER devices were completed and dispatched for fabrication. Design of the clock recovery circuit was started, as well as work on the testing aspects of the integrated circuits, the subsystems, and the control interface.

The selection of the 2.5 Gbit/s STM-16 signals from the optical receivers is required prior to demultiplexing to STM-1. This function is carried out by an expandable non-blocking 12×12 switch matrix chip set designed in R1036. The chip set was fabricated by SGS-Thomson on a high speed bipolar process developed under the ESPRIT 2 programme. The devices were tested to a high degree at wafer sort so as to maximise the yield of packaged devices - important because of the high cost of the packages which are multi-layered ceramic packages incorporating controlled-impedance transmission lines. A total of eight packaged devices of the 12×12 switch matrix were found to pass the DC functional test, and six devices passed 90% of the AC dynamic testing; the drop-out in dynamic testing was due to instabilities in the device processing. However the results achieved were extremely good. Fig. 8 shows a comparative test between the input waveform and the selected output. This shows that the increased jitter is only 10 ps. Further tests on crosstalk between channels shows that it contributes only 10-12 ps extra jitter. The devices were mounted into the matrix submodule.

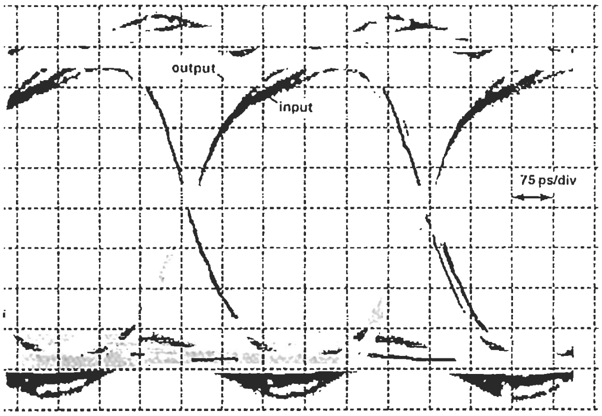

Fig. 8 - 12x12 2.5 Gbit/s matrix IC: comparison of input and output waveforms

Also during the second year a PCB able to be configured in both 12×12 and 24×24 configuration was designed. Tests were started as soon as I/O buffer chips and crosspoint ICs were available. The major objectives of the tests were to validate all connection points, to evaluate performances of matrix ICs in different configurations such as cascadability facilities, signal distribution, influence of crosstalk, etc, and to determine the maximum size of a switch based on such an IC.

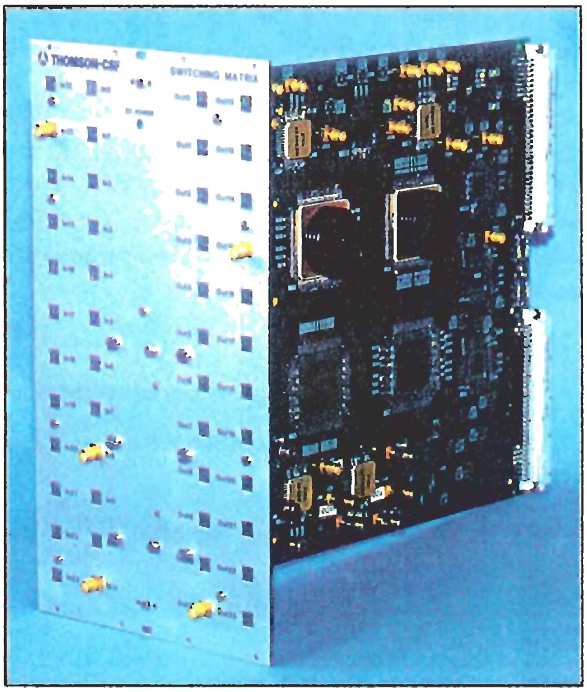

Fig. 9 - Switch matrix test board

Fig. 9 illustrates the board designed within this project. All connections are performed on the front panel by means of SMA connectors (48 connections!) and between the front panel and the PCB involves a multi-way RF connection. Fig. 10 illustrates the results obtained on a 2^{23}-1 PRBS when all the eleven unselected inputs of the switch are loaded by uncorrelated perturbation signals. Similar results have been obtained for other configurations such as correlated perturbations and signal distribution. It is important to note the good quality of the eye pattern and a total jitter lower than 80 ps.

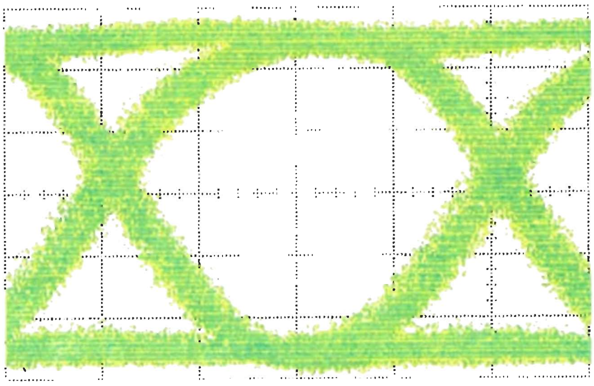

Fig. 10 - Switch matrix: output 2.5 Gbit/s PRBS

During the third year, a system demonstrator was constructed using the STM-16 multiplex and demultiplex subsystem boards, and it was demonstrated at RAI Research Centre in Turin. Due to a problem with the STM-1 adapter ASIC, the frequency adaptation processor was unable to operate fully in Turin in March 1995, but was fully demonstrated in Oslo in September 1995. These modifications were also made to reflect ongoing changes to the ITU and ETSI standards on pointer processing, and the device was fully evaluated during the Project.

The board designs of the multiplexer and demultiplexer were refined so as to optimise their performance. The multiplexer board was redesigned to include the new STM-1 clock recovery chip completed during the third year. This is a low-power, low pin-count device and is required on the fully populated multiplex board due to the restriction on space and power. A daughter board was also designed for the multiplexer, which is used to buffer the 2.5 Gbit/s serial output stream to allow up to 3 lasers to be driven from this board. This adds a level of redundancy by allowing diverse routeing of the optical train, improving the system's tolerance to single-point failures in the network. A multiplexer is shown in Fig. 11, and a demultiplexer in Fig. 12.

For the final design of the 4-channel demultiplex board, system tests have shown that bit-error rates of less than 10^{-12} are now attainable on the 2.5Gbit/s link.

A further single-channel demultiplex board was also designed to include the 2.5 Gbit/s clock regenerator module. The new board has the advantage of being a totally integrated system, and connects directly with the optical receivers or 2.5Gbit/s switch. The board has been designed into a half-height (3U) module, and selects up to 8 STM-1 channels from the STM-16 input data stream.

Control of the boards is carried out via a daughter board that plugs into a DIN connector. This then communicates with the control network over a serial line based on the Intel BITBUS protocol which is a subset of SCSI. The control interface was evaluated, and configuration of the network along with error reporting and system statistics can be transmitted to a remote PC.

WP2.2

Optical transmitters

Initially, several types of laser chip were examined; that finally chosen was a distributed-feedback (DFB) device.

Of the modulator chips investigated, the only one suitable was the LG1608A from AT&T, which has the advantage of differential outputs. Northern Telecom have developed two semi-custom silicon ICs to perform ancillary functions such as temperature control and alarms; computer modelling showed that these would integrate well into the R2001 transmitter, reducing the size and

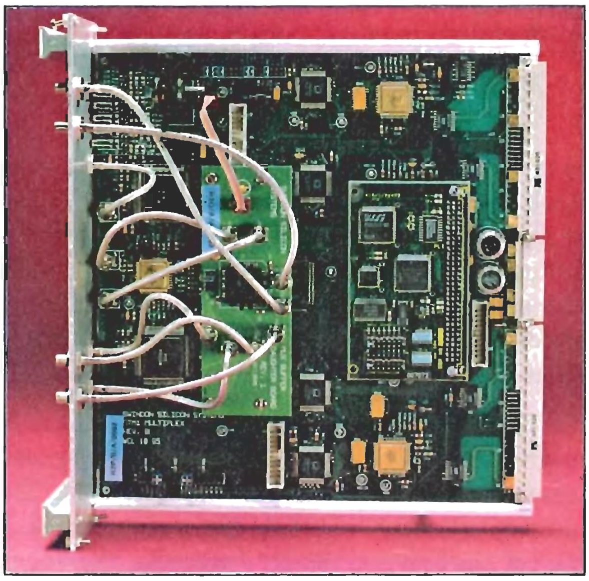

Fig. 11 - Electrical multiplex board: 4 STM-1 channels in, 1 STM-16 channel out

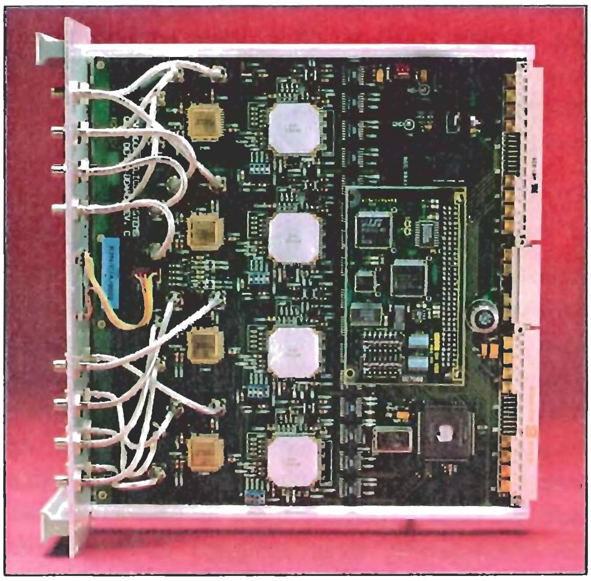

Fig 12 - Electrical demultiplex board: 4 STM-16 channels in, 4 groups 4 STM-1 channel out

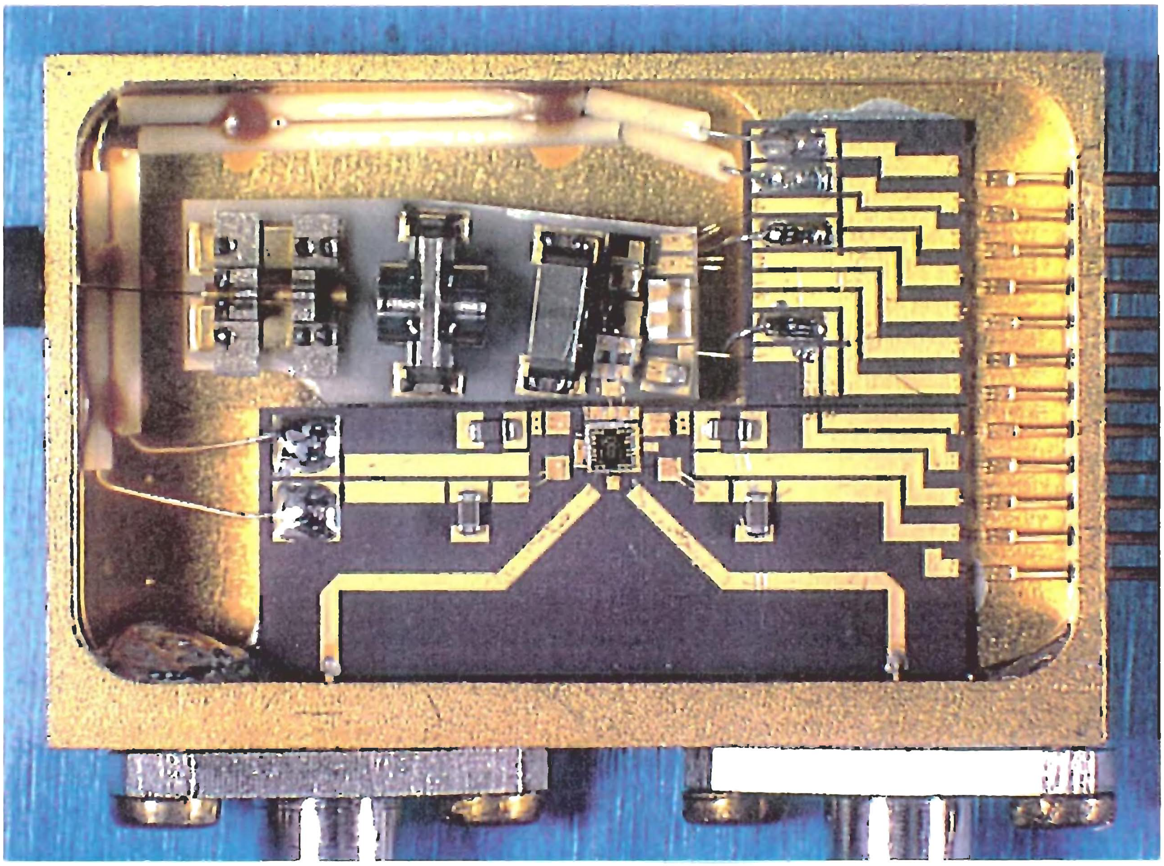

Fig. 13 - Complete DFB laser assembly

cost of the unit.

The performance of the first-version prototype was poorer than expected in two areas: fibre-coupled optical power, and heatpump performance. The final version was therefore designed with careful attention to both. It is shown in Fig. 13 and contains DFB laser, optical bench, lens, optical isolator, optical fibre, Peltier heatpump, and modulator IC. The problems were solved as follows.

Power coupled to the fibre

The inability of the first-version prototypes to achieve the target output power of 0 dBm has been attributed to three causes. Firstly, the optical path through the multiple elements of the optical isolator was unknown, resulting in the DFB image lying on the extremes of the fibre location range. Secondly, optical modelling has shown that the object distance of the aspheric lens is more critical than had been expected, and a revised lens holder has consequently been designed in conjunction with the development of a two-step lens-positioning process. Thirdly, the first-version prototypes did not feature a skewed optical path to match the angled polish of the optical fibre. The correct skew has now been adopted.

With these changes the two hermetic cavities coupled +1.7 dBm and +2.5 dBm at 25 mA DC above threshold (maximum peak modulation current available from the IC is 50 mA). The system requirement is 0 dBm.

Heatpump

The first-version prototypes featured open-style packaging for ease of testing and the resulting ingress of ambient air was by far the largest contributor to the poor performance of the heatpump. This is inherently avoided in the final version since it uses a hermetic cavity. The thermal performance has also been improved by using a different bench material.

Molybdenum was originally used as it is non-magnetic (a requirement of the isolator) and reasonably expansion-matched to ceramics. The industry standard material for such thermally-critical pieceparts is rapidly becoming aluminium nitride, which has a thermal conductivity of 180 W/mK as opposed to 135W/mK for molybdenum, and so the decision was taken to

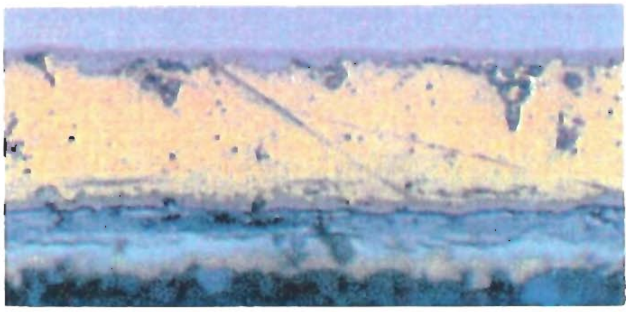

Fig. 14 Early attempt to attach kovar straps to aluminium nitride bench, showing cracks

adopt it. It is non-magnetic but cannot be laser welded; this caused problems in attaching kovar straps so that components could in turn be attached to the straps. Initial attempts used gold-nickel-gold sputtering and then a gold/germanium eutectic to attach the kovar. This produced variable results with brittle nickel/germanium intermetallics growing in a way which could not be attributed to process parameters, even after considerable effort. The intermetallics were prone to sudden failure by the propagation of cracks (Fig. 14). A solution was found which involves co-firing patterned tungsten with the aluminium nitride from the green state. The straps could then be attached by the use of high-temperature braze, e.g. copper/silver. This is the technology which was finally adopted.

Another change which was made to improve thermal (and hence wavelength) control was the relocation of the feedback thermistor from the bench to the DFB carrier.

With these changes, it has been found that the heatpump is able to hold the laser at 20°C when the ambient temperature is 50°C. Experience of other laser transmitters shows that this is as much as can be expected from a single-stage heatpump.

The low-frequency circuitry which performs the laser pre-bias control, thermal control, and alarm and monitoring functions of the transmitter has been designed and laid out on a double-sided PCB, and can be seen together with the hermetic cavity (unlidded) and module aluminium casing in Fig. 15.

Final-version laser transmitters were first successfully employed during the R2001/R2065 demonstration at RAI, Turin with a typical optical eye (unfiltered) as shown in Fig. 16.

The laser status alarms are indicated on the module front panel; with the disable function, they are also conveyed to the on-board BITBUS interface card so that the laser may be interrogated by the system controller. The status

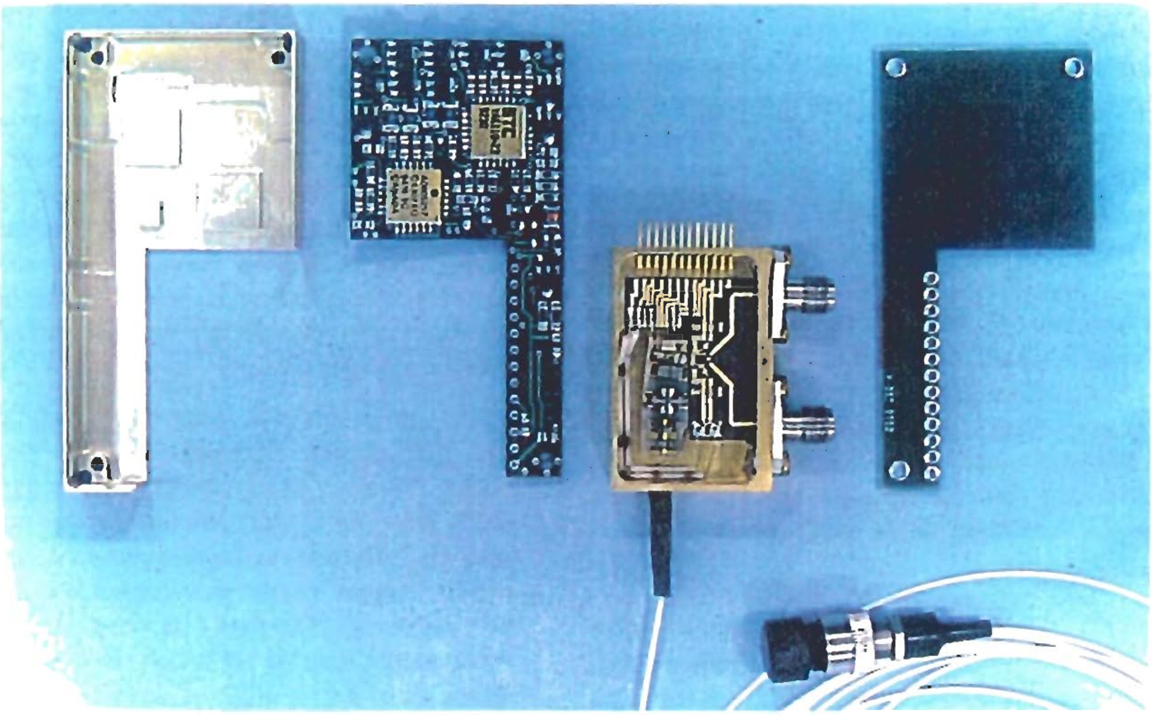

Fig. 15 - Complete laser assembly including control circuitry

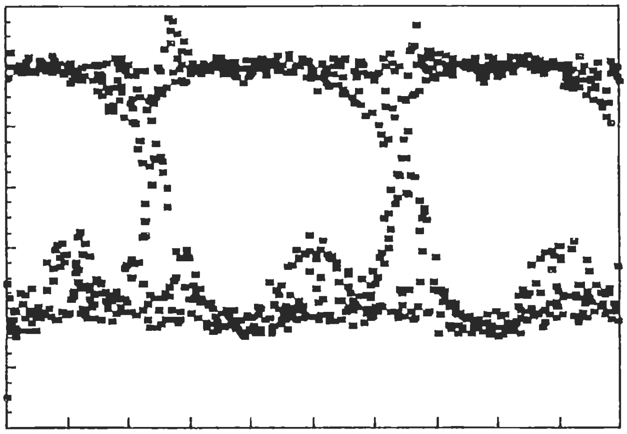

Fig. 16 - Eye pattern of laser transmitter

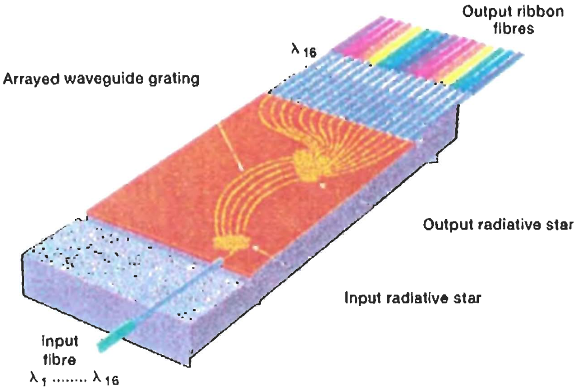

Fig. 17 - Diagram of arrayed-waveguide WDM

flags are as follows:

Optical power high
Optical power low
Temperature high
Temperature low
Laser disable
Laser bias approaching end of life limits

The drive circuitry has been designed to provide the laser transmitter with power supply conditioning. The dual-rail supply is cross coupled such that if one rail is interrupted then the other is disconnected (the rails will be provided by separate PSUs in the pilot installation). The rails are soft started and stopped by the circuitry to prevent transient damage and instability in the laser control functions, and the circuitry itself soft-starts to prevent overloading of the system PSUs on power-up.

Since heatsinking is critical to the performance of the laser transmitter, the metal housing has been used to the best effect possible. The pressed aluminium cover of the housing has been employed as the heatsink for the laser, and extra heat load has been minimised by heatsinking the dissipation of the ancillary circuitry elsewhere on the metal housing.

WP2.3

Optical demultiplexer (integrated)

The main technical contribution of BNR Europe Limited to RACE 2001 was in the design, development and fabrication of planar waveguide wavelength demultiplexer (WDM) devices. Activities have included modelling of waveguide and component behaviour, photolithographic mask design, fabrication, fibre pigtailing, packaging and testing of components.

The silica-on-silicon planar waveguide radiative star can be used as a building block for a family of WDM devices, multiplexers, demultiplexers and wavelength routers. The basic demultiplexer device, comprising two radiative stars, separated by a phased array of waveguides is shown in Fig. 17. This configuration can function as a wavelength multiplexer or a demultiplexer, but for use in this Project, only its operation as a demultiplexer was considered.

After a number of design and processing iterations, a best design was identified and used in an integrated photolithographic mask set (i.e. with a V-groove mask to locate input and output fibres). From this mask set a prototype fibre pigtailed and packaged 1×8 WDM demultiplexer device was completed and delivered to GEC-Marconi for evaluation in the system test bed and for trial in the pilot installation. Its performance is detailed in Fig. 18.

Environmental tests have been carried out on a similar fibre-pigtailed and packaged WDM device. Over a temperature range from -55°C to +125°C, the variation in loss was less than ±0.3 dB, and the corresponding variation in output channel centre wavelength was 0.01 nm per degree C. The latter is very close to the fundamental limit of all WDM devices based on silica, set by the variation of refractive index with temperature. In addition, the shift in the centre wavelengths of the output channels for different polarisations of the input (polarisation

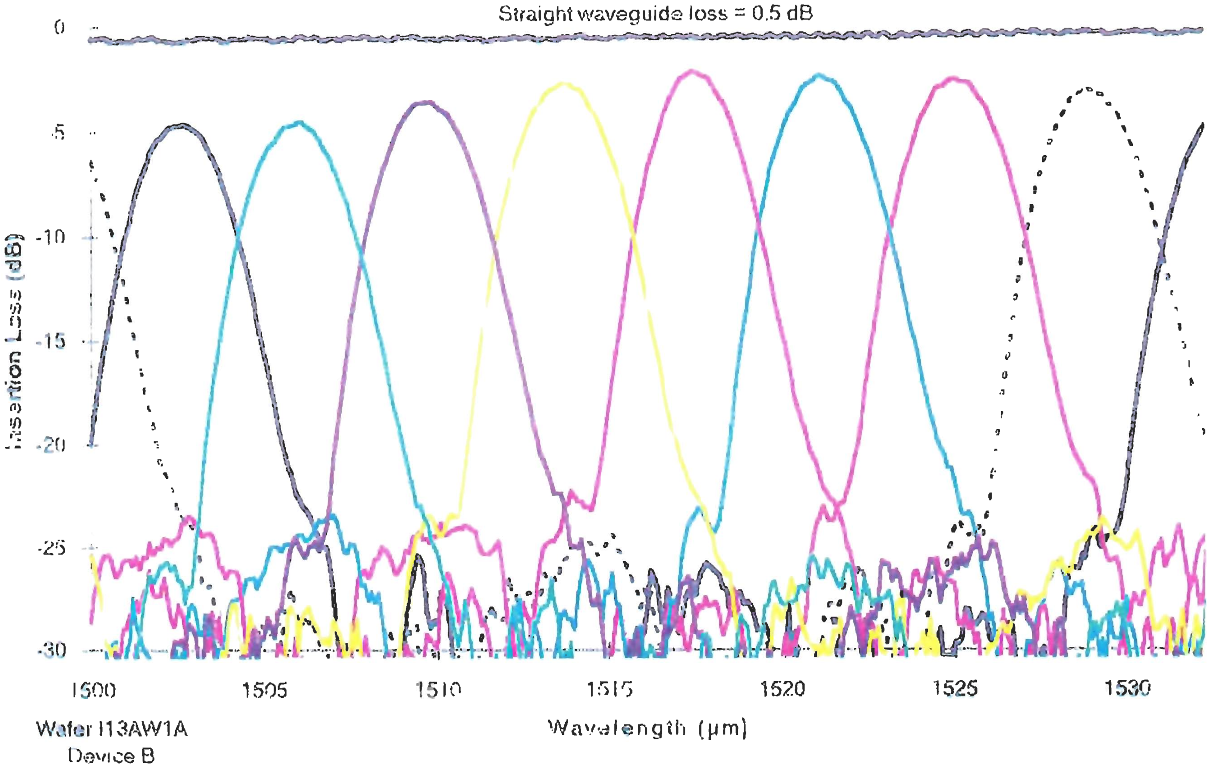

Fig.18 - Insertion loss v wavelength of a 1x8 WDM before connectorisation

dispersion) is less than 0.15 nm. These are all excellent results.

With the aim of improving inter-channel crosstalk performance, a number of new device designs were also studied, masks made and chips fabricated. In order to accommodate more devices on each wafer, 4-channel designs were investigated (earlier results have shown that the number of channels can be increased to 8 without a degradation in performance).

A figure of -28 dB crosstalk has been achieved with these latest designs, as shown in Fig. 19. This is a major improvement over the earlier results (-20 dB), and meets the level of crosstalk typically requested by system designers, -25 dB to 30 dB.

With respect to cost, the potential savings using silica-on-silicon technology are very considerable. In quantity production, fully fibre-pigtailed and packaged silica-on-silicon 1×16 demultiplexers (4 nm channel spacing) are expected to cost a few hundred ECUs each, compared with more than 10,000 ECUs for a comparable bulk-optics WDM.

WP2.4

Optical demultiplexer (bulk)

Within R1036, the initial WTDM Project, Jobin-Yvon manufactured 16-channel wavelength demultiplexers with a 4 nm channel spacing and with a ratio (*R*) of channel width (at 90% of maximum) to channel spacing of 0.35. As far as is known to the Project, this is better than any results obtained in other laboratories at equivalent low losses (<2 dB) and crosstalk (<-20 dB).

However, theoretical and experimental analysis during the first year showed that *R* can be increased by between 10% and 20%. This improvement could be taken advantage of in several ways, e.g. it could allow the use of more channels with same laser specifications (our main objective) or smaller channel spacing (to stay within the spectral range for optical amplification). Alternatively, at the present 4 nm wavelength spacing, some relaxation of laser specifications would be possible.

Two experimental demultiplexers were made during the first year:

- 4 channel all single mode WDM with 0.5 nm spacings.

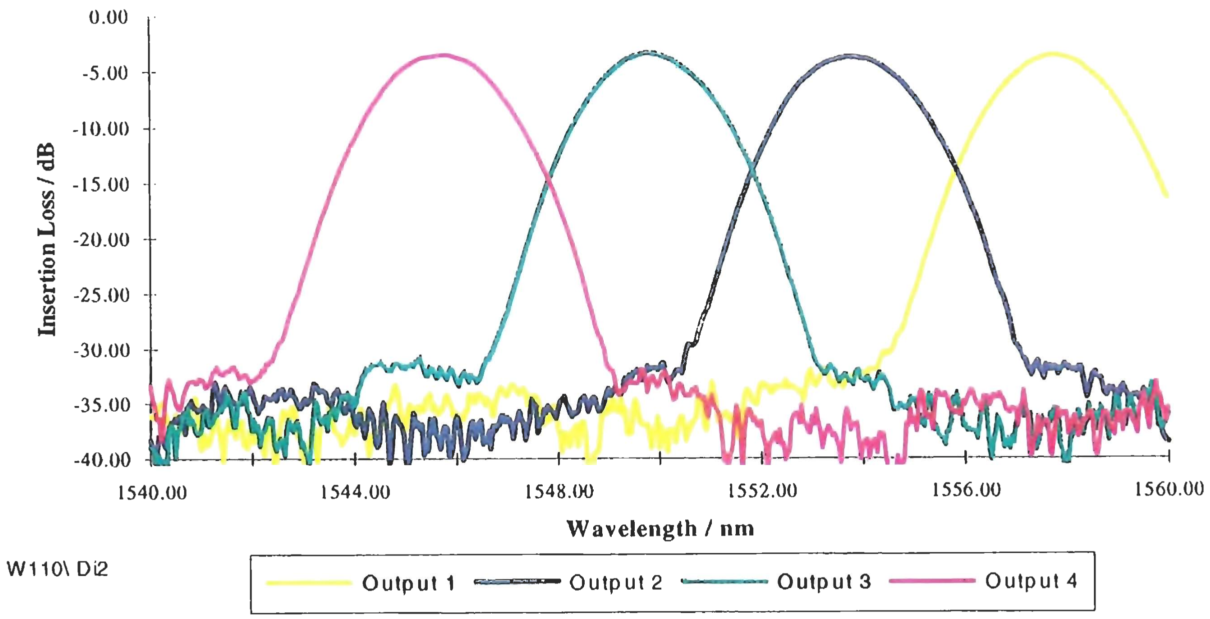

Fig.19 - Insertion loss v wavelength of a 1x4 WDM before connectorisation

- up to 20 channels all single mode WDM with 1.6 nm spacings.

Two 16-channel demultiplexers were made with 0.4 nm relative shift on all channels. Two demultiplexers with such shift between them can be used for special error feedback for simultaneous monitoring of laser wavelengths.

During the second yet lower results for insertion loss were obtained: 2.5 dB on a six-channel all-single-mode-fibre mux/demux, and 1.8 dB loss on an eighteen-channel channel single-mode to 50/125 μm graded-index 2 nm spacing demux, better than the R1036 result of an insertion loss of 1.9 dB for a sixteen-channel 4 nm spacing WDM.

A theoretical optimisation of the polarisation response of the demultiplexer was carried out using electromagnetic theory: this study indicated that an optimised R2001 demultiplexer from Jobin-Yvon could give only 3% variation from TE mode to TM mode.

Up to 20 highly reproducible channels were shown to be possible in a 2 nm spacing demultiplexer; the figure of merit *R* reached 0.7 in some cases.

During the third year, further new ground was broken in the field of optical demultiplexer design and fabrication. Devices were produced with outputs on up to 41 single-mode fibres, with wavelength spacings down to 0.5 nm, and with losses less than 1.5 dB. Crosstalk at 1 nm spacing was better than -30 dB (typical -38 dB), and peak wavelength variation less than 0.02 nm between -20 and +60°C.

During the fourth year, a fibre holder was made which is expected to form the first step towards a 125-channel single-mode to single-mode wavelength demultiplexer.

For direct use in the Project, two single-mode to single-mode WDMs with 16 channels at 4 nm spacing and two with 16 channels at 2 nm spacing have been delivered, as well as one with 20 channels and 1 nm spacing. Crosstalk was much better than specified; values of -48 to -60 dB have been measured. Loss measurements on these WDMs have shown no change after temperature cycles between -20° and +60°.

A Peltier temperature stabiliser was developed which allows (for example) the 20-channel WDM to operate within specification between -20° and +60°. The device has also been shown to withstand shocks according to the Norm. C 20.608.

The 41-channel device is shown in Fig. 20, with the Photonics Circle of Excellence Award which it won in 1995.

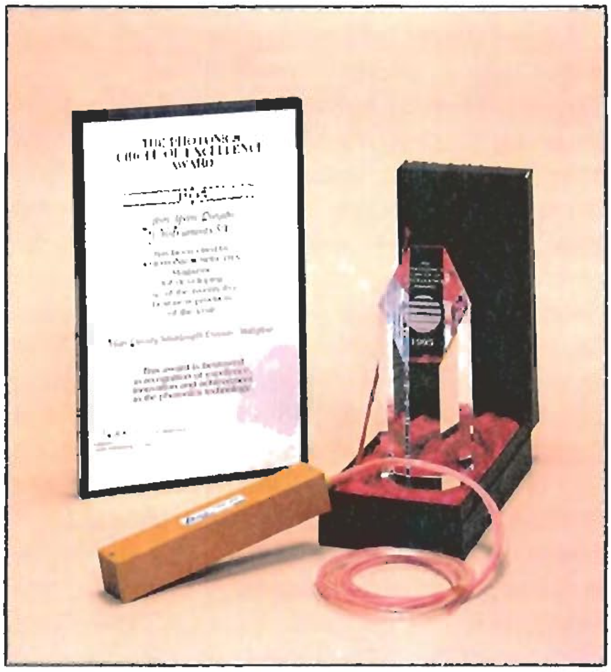

Fig. 20 - 41-channel bulk optics demultiplexer with 1nm channel spacing; shown with 1995 Photonics Circle of Excellence Award

WP2.5

Optical receivers

New work has built on the achievements of R1036, where optical receiver modules were developed to operate at 2.48832 Gbit/s (the STM-16 rate), with clock recovery, and with a sensitivity better than -30 dBm. However, the physical construction of these modules was unwieldy and unsuitable for production on the scale required.

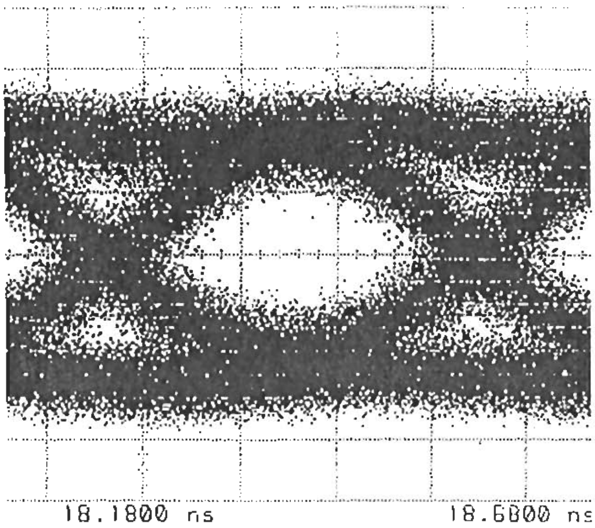

Fig.21 - 2.5 Gbit/s eye pattern measured at -33 dBm received power

Emerging ultra-fast gallium arsenide components such as exclusive-OR gates, D-type flip-flops and data distributors were first evaluated for an updated design of the clock recovery module. The main targets of any new design were to reduce the size and cost of the module but to keep the original performance level. The components tested had very good performance, for example rise time and fall time (10% to 90%) lower than 90 ps and additional jitter so low that it could not be measured; unfortunately the costs of these components were rather high.

A new type of transimpedance preamplifier based on discrete components was simulated and a breadboard realised. The plot in Fig. 21 shows that the eye pattern for an optical level of -33 dBm is excellent. A new two-channel board, based on the new design of the optical receiver with clock recovery was made. All of the components were mounted on the same substrate, and shielded boxes were used to avoid coupling effects between low noise analogue functions such as the transimpedance preamplifier and high level functions such as the clock recovery. Each channel comprised an avalanche photodiode (APD) detector, a transimpedance preamplifier, a broadband AGC amplifier, and a clock recovery function.

Evaluation of this board was performed and demonstrated a quite significant improvement in performance compared to the R1036 design. First results showed a sensitivity of -33 dBm and a dynamic range of 22 dB.

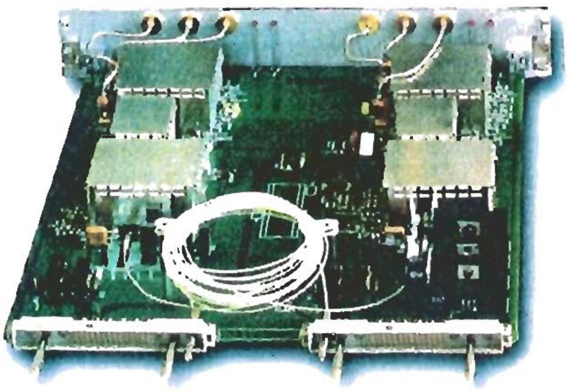

Fig.22 - 2.5 Gbit/s optical receiver

Thermal performance was satisfactory, and all boards conformed to the CCITT Rec. G958 criterion for jitter. Also encouraging was the reproducibility, both for the pilot installation and for other possible industrial applications.

This STM-16 optical receiver (shown in Fig.22) was evaluated in 1994 by France Telecom with satisfactory results; subsequently, three more sets were installed in an experimental optical STM-16 system at CNET Lannion. Two sets were supplied for the Oslo installation, where they were thoroughly proved in public.

WP2.6

Control

The control system was split into two layers, the Application Control layer, (the man-machine interface) and the Network Control layer (the equipment interface). This split, which was foreseen in R1036, allows the layers to be developed and tested almost independently; it also allows the design of different Application Control equipment for different applications or different customers.

At an early stage, agreement was reached on the functional specification of the interface between the network control layer and the application layer. The interface that has been defined is based on a functional abstraction of the basic switching and routeing function of the network. The network control layer hides all details of routeing from the application control layer, including alternative routeing in case of component failure. The result is that the application control layer is independent of the actual topology and configuration of the physical network. The network control layer translates between this abstract model and the physical network.

In principle, the network was designed to be non-blocking, i.e. for all paths to be independent. However, it was foreseen that this non-blocking property could not be maintained in case of a major network failure. Although the network control tries to reroute traffic around the failing component as far as possible, the loss of capacity will probably prevent some of the connections from being maintained. To arbitrate between the various connections in a sensible way, a priority mechanism was incorporated, such that, for instance, on-air circuits will have the highest chance of being sustained.

Experiences in R1036 revealed the unsuitability of a parallel interface bus for the interconnection of control nodes and the various switching matrices, demultiplexers etc. After some investigation, Intel Bitbus was selected as the standard for connecting remote panels into the AC layer network and was later proposed as the general interfacing standard for inter-module communication within the overall control system. To achieve acceptable response times, it was necessary to control the interfaces by means of high level messages that did not contain more data than strictly necessary, and to pack as much control information as possible into a single message (instead of sending separate messages). A demonstration system comprising of a number of keypads with alphanumeric displays was constructed. For the final system, a network of IBM compatible PCs formed the user interface hardware.

The control software has the capability of providing several levels of access to preserve the security of the overall system, to safeguard transmission and other vital paths, and to prevent unauthorised access to programme material. The system is user-friendly, and provides for operators a touch screen showing the signal routes as they are set up; for maintenance engineers, a screen shows network status as well as a comprehensive display of faults and impending faults.

The software has been further developed to cater for a wide range of system configurations as well as that of the pilot. For the NRK installation, a COMMSERVER capable of supporting 4 Operator Workstations has been configured. This may be expanded to 25 or more if required. The system now supports up to 14 individual levels of routeing. The OIU interface is via an RS232. The system at NRK can interface to a further 7 OIUs before additional hardware is required.

WP2.8

User interface

The signals carried and routed by the WTDM network fall into two categories: audio and ancillary signals, which require relatively low bitrates (less than 6 Mbit/s for a complete channel) and video signals, which require up to 270 Mbit/s for standard digital component format.

Low bitrate (audio and ancillary signals)

The user signals group (USG) comprises the following signals:

- one AES-EBU frame, which contains the digital audio signal at a bitrate of 3.072 Mbit/s, coded to conform to CCIR Rec. 641 (AES3: 1992)
- one high-speed serial channel at 2 Mbit/s with a V11 interface
- one RS422 serial channel, which realises the synchronous/asynchronous adaptations and occupies a 64 kbit/s channel
- one analogue I/O phone link, which is digitised to conform to CCITT Rec. G711 and which occupies a 64 kbit/s channel
- one ancillary channel of 8 bits sampled at 8 kHz and occupying 64 kbit/s in the VC2

Development has been successfully completed.

Furthermore, the collaboration undertaken between this Partner (ITIS) and the developers of the STM-1 adaptor (Swindon Silicon Systems) during its definition phase, has expanded device functionality and led to an interface which is easier to use. In particular, the USG equipment can now be inserted into an STM-1 chain, playing the rôle of an add-drop multiplexer of SDH subchannels.

As regards the user signals themselves, the USG equipment has demonstrated its ability to carry transparently over an SDH network all of the required signals: digital audio ('Rec. 647'); speech (G711); synchronous stream (X21: 2Mb/s); asynchronous stream (RS422: 38.4 kbauds).

This set of signals allows broadcasters using a WTDM network to exchange all of the signals that they generally use in addition to their audio and video programme material. Furthermore, the linearly-encoded audio used in USG equipment ensures that quality is not degraded by many passes through the network.

Tests with standard audio equipment have revealed that the method used to recover the service clock at the receive side does not introduce significant jitter, and that the received signal conforms to the AES3-92 specifications. Thus, the resynchronisation process on the received audio does not introduce signal degradation.

Operational reliability and fault tolerance of the equipment has been enhanced by on-board software which monitors the input signals, and where possible implements self-correction of fault conditions; an example is the internal generation of an STM-1 frame when the input frame is lost.

Fig. 23 shows a stack of four USG transmitters and four receivers. The units have their own internal power supplies.

High bitrate (video signals)

To reduce costs and increase system flexibility, a single stand-alone rack has been designed to carry one STM-1 link as shown in Fig. 24. This video codec can run in three modes, depending on input signals:

1. analogue PAL:
    - sampling frequency: 13.5 MHz free-running or locked to a reference black-level and burst
    - sampling resolution: 10 bits
    - whole video frame transmitted — fully transparent
2. ITU-T Rec. 656 digital component with compression:
    - video components coded through a 6 to 8-bit/sample DPCM algorithm
    - horizontal blanking: digital embedded audio transmitted without compression
    - vertical blanking: content (ancillary data, test lines, etc.) of 3 lines/field transmitted without compression
3. ITU-T Rec. 656 digital component signals without compression:
    - the whole 270 Mbit/s stream is split into two 135 Mbit/s streams, carried on two separated STM-1 channels. The two receivers are coupled together to provide the entire 270 Mbit/s video signal

The video mode can be selected by either the front panel control or by the Bitbus interface (remote mode).

Detected alarms are displayed by LEDs on the front panel, and are also accessible to the control network.

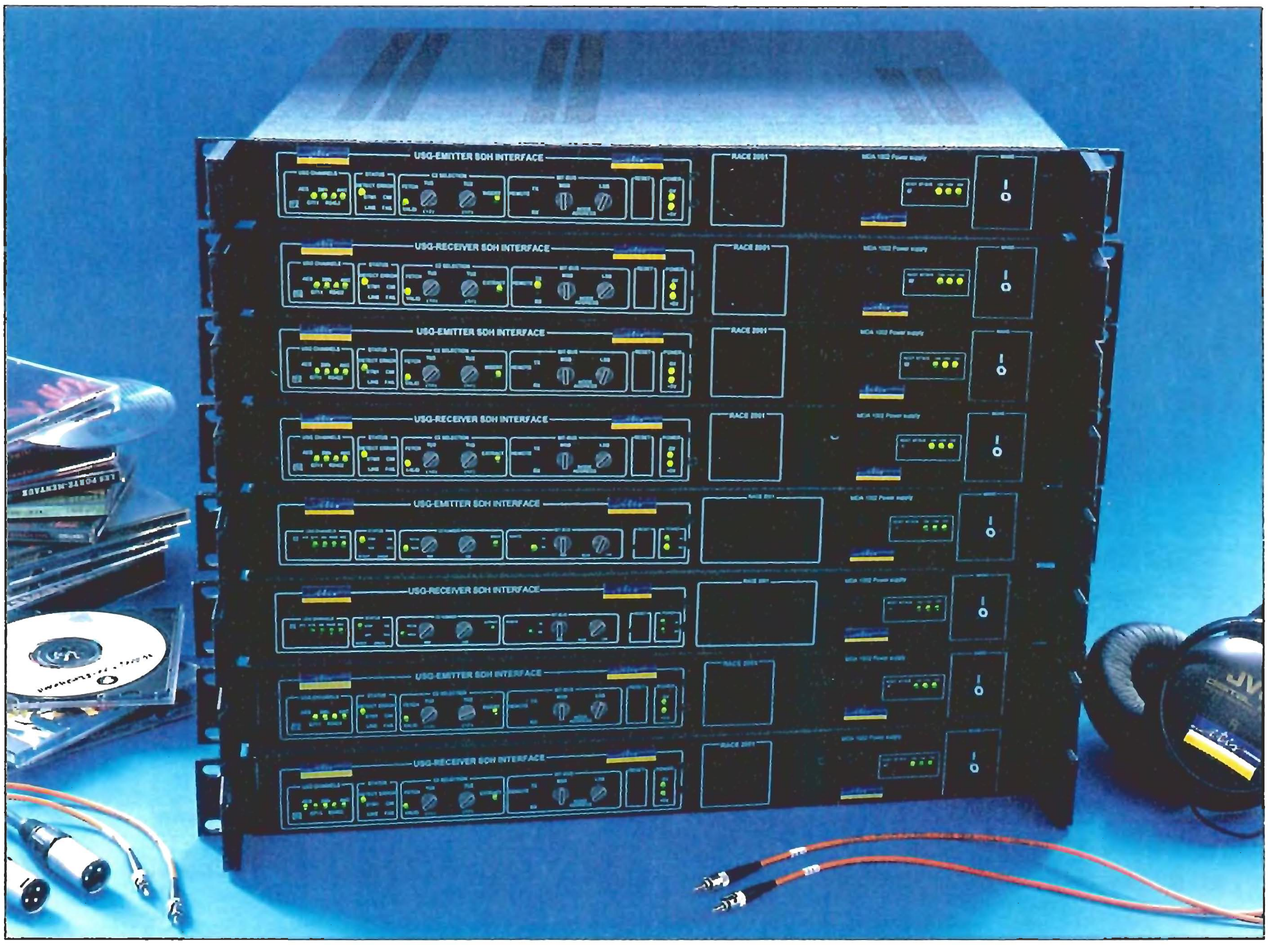

Fig.23 - Stack of four STM-1 USG transmitters and four receivers

The remote-control interfacing operates as follows. On-board management software for configuration and alarm detection is separate from that for Bitbus control. The two routines exchange useful information through a common table implemented in a RAM area, which serves as a 'mail box' that is regularly checked by both.

WP3.3

Optical switch

Overview

The use of EOTF-based optical switching as a substitute for electronic switching in the R2001 system could provide an advantage by a reduction in the number of 2.5 Gbit/s electrical switching and clock recovery circuits. EOTFs have the potential to providing a transparent and therefore future-proof channel selection. To achieve this optical switching subsystem, the passive wavelength demultiplexer needs to be replaced by the optical switch which would occupy its place in the system optical power budget. The optical switching subsystem comprises an EDFA, 1:N optical splitter, and N EOTFs, where N is the number of outputs to the switching subsystem (Fig. 25).

The design of an EOTF is complicated by three significant factors. Firstly, the wavelength response of a lithium niobate device is temperature dependent. This sensitivity can be characterised as a tuning effect of ±0.7 nm/°C. Secondly, the wavelength response of the device must be accurately tuned to a required channel so as to produce an insertion loss variation of less than that required to meet the overall specification. Thirdly, this must result in the cross-talk figure required.

A temperature control objective of ±0.64°C was set to reduce the effects of cross talk arising from the EOTF. This figure corresponds to a tuning capability of ±0.5 nm. Temperature control was achieved with the design reported here by a nichrome (NiCr) planar heater which is deposited on the reverse side of the lithium niobate substrate. A chip thermistor on the EOTF surface drives a temperature control circuit.

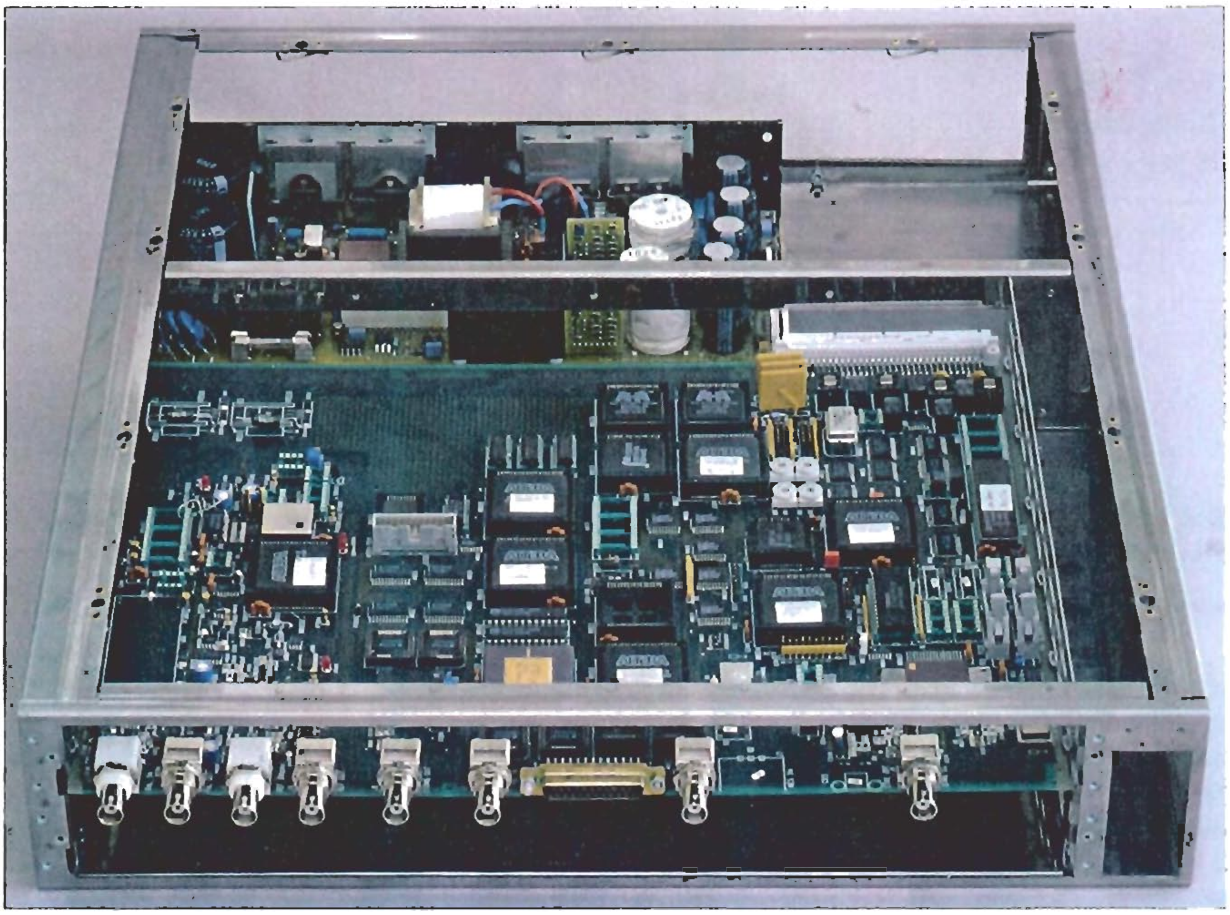

Fig. 24 - STM-1 video codec

Implementation

In the EOTF implemented for the pilot installation, polarisation diversity was achieved by pigtailing the EOTF with polarisation maintaining optical fibre from two polarisation splitters (manufactured by JDS) rather than by using integrated polarisation diversity couplers. Within the EOTF package, an alumina substrate carries the lithium niobate device as well as providing the usual bonding sites for electrodes and also provides contact to the underside of the substrate for the purpose of allowing electrical current to the NiCr heater. A number of thermistors placed along the length of the EOTF substrate allow measurement of temperature profile.

A power supply board provides -8V and +8V. A Bit-Bus interface circuit was developed to drive the mode converter lines. Voltage tuning can provide optimum mode conversion for each EOTF packaged. The interface incorporates two EPROMs with a complex output for the purpose of achieving the required voltages.

The tuning voltage circuit provides adjustable voltages for the complete combination of output voltages from the circuit. Nominally, the tuning thus provided should be ±2 nm.

The EOTF is controlled via a Bit-Bus interface which provides three control lines for the selection of wavelengths. At the time of the NRK demonstration this was all that was required since the network included only one EOTF. However, the controller has the capability of providing control lines for device selection should more than one device be required. A 4-laser WDM system was used to demonstrate switching with a worst case extinction of 18 dB. The insertion loss of the device is less than 3.2 dB fibre to fibre. The module includes all electronic circuits for controlling the optical switch, together with a Bitbus interface to the overall network control system..

The use of the EOTF as an optical filter has been proven at the NRK installation; however, its integration with appropriate polarisation diversity couplers means that it has the potential to be used as a routeing element for a switched

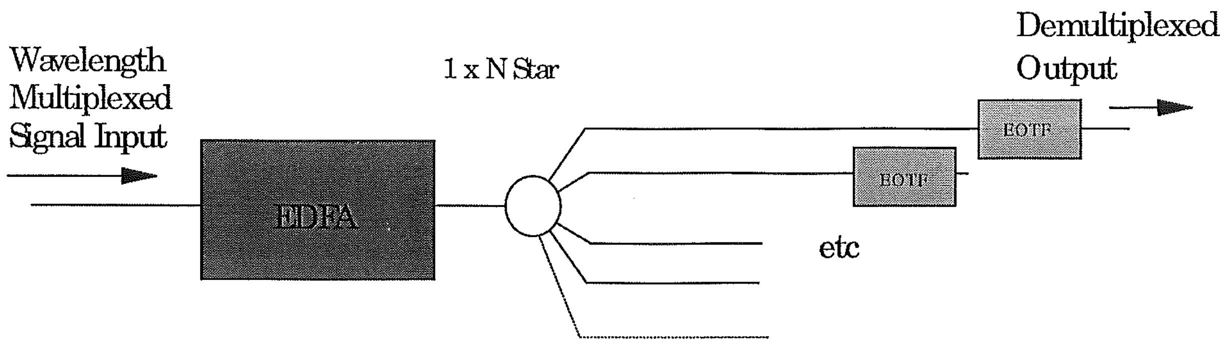

Fig.25 - Optical switching subsystem

optical network. This application is discussed in the following section.

Multihop architectures

If a network architecture uses an optical transport layer which has the capability of combining WDM with ATM then there is the possibility of introducing redundancy and reconfigurability to that network. A study and modelling have been conducted to demonstrate this and have been applied to existing physical optical networks.

The operating principle is termed 'multihop' and it harmonises ATM packet switching with WDM and wavelength reuse. The concept of multihop networking is by no means a new one, and the principle is that rather than data travelling directly from a source node to a destination node, data is passed from one node to another until the required destination is reached. The advantage with this system is that data packets can be transported not simply along a single route, but along a number of parallel routes. As the communication channels may now be in parallel, then a higher network capacity is potentially available. Thus a shuffle net (for example) can be provided across an optical star or, as reported in other literature, the virtual topology of a shuffle net can be implemented over a physical architecture comprising a bus with 16 fixed-wavelength transmitters and receivers.

An important note here is that if tuneable transmitters are used, then there is no strict requirement for the virtual topology to remain regular or even fixed through the lifetime of the network. With the multihop technique, it becomes possible to optimise and reconfigure networks in the event of (say) asymmetric loading. For these cases, the virtual topology would be achieved by rearranging a single-wavelength network (Fig. 26) to form the WDM of Fig. 27(a) by reconfiguring an EOTF of the form developed and modelled under the R2001 programme with fixed-wavelength receivers over a broadcast medium. The physical topology may then be reconfigured to form the eight-node shuffle net of Fig. 27(b). It is important to appreciate that the physical network and connections remain the same, although the implementation of three (reusable) optical wavelengths, 8 Sinctay Quad EOTFs (with polarisation diversity couplers) are employed with 8 ATM switches. It may be noted that the number of hops necessary to allow communication between any two nodes for this configuration is one or less, so that the capacity of the network is maximised.

Further development work

The EOTF used at NRK was a single-ladder device which gives a 4-wavelength filtering capability (Fig. 28). Advanced designs based on the NRK EOTF have been modelled and mask sets generated. For example, a dual-ladder EOTF offers the possibility of 8 wavelength optical filtering with 4 nm spacing, through the application of a tuning voltage calculated to be 100V. The optimum operating voltages for quad-ladder devices have also been designed and modelled. Mask designs have been devised to fabricate a range of dual and quad devices on a single wafer to allow the study of various designs. Careful attention to layout allowed a high yield and easier fibre pigtailing.

A range of other investigations have been carried out into the very complex properties of lithium niobate, and have provided some insight into the possible means of producing more reliable and stable devices.

5 STANDARDS IMPACT

The Project implements fully the CCITT Recommendations on SDH; not only those essential to multiplexing, but also those concerned with performance of SDH equipments, such as G.957. This work continues to contribute to the validation of these standards; for instance, design work on ICs has uncovered ambiguities in CCITT Recs G.707-709 which have been discussed with representatives of the standards committees.

Standards on optical safety, notably BS EN 60825:1992 and ANSI Z-136.2:1988 have been important in establishing optical system specifications. The Project worked to the relevant EC standards, but using where necessary a US standard for guidance in situations not explicitly covered by EC standards.

The work in this project on a backplane version of the EC connector from R1089 which has already been standardised (EN 86 211-001) will enhance the position of the EC connector on the market. The connector has been chosen by France Telecom and by Belgacom.

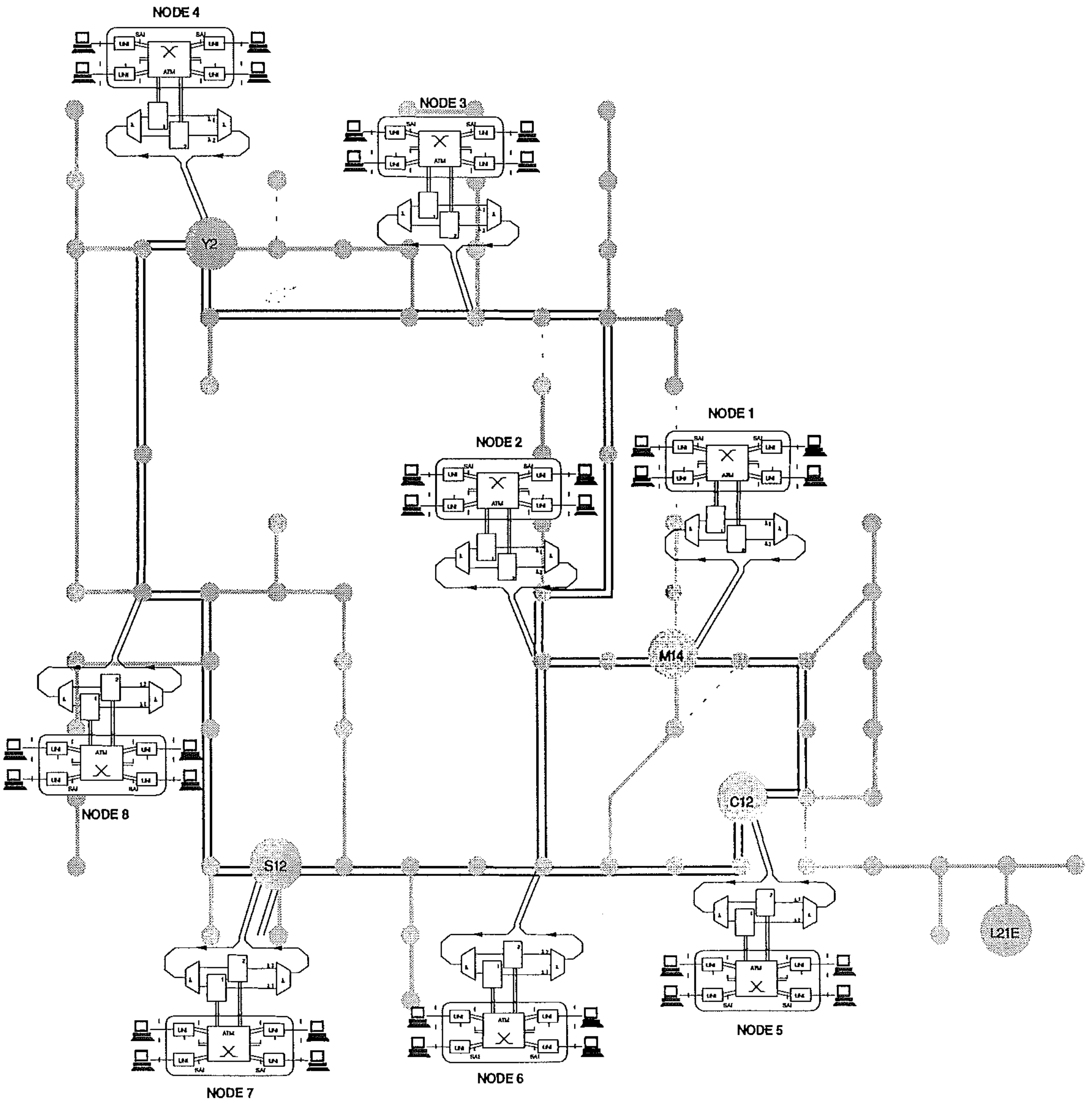

Fig.26 - Physical ATM network with eight ATM switches, an optical transport layer and one optical wavelength

Contributions based on the work of the Project have been made to STG3.3, particularly in the area of wavelength allocation for optical systems. Contributions have also been made to a RACE workshop; this work will result in modification of the CPR E334.

The mapping of broadcasters' signals into SDH containers is an area where the work of the Project is also expected to contribute to standards.

The high-speed multiplexer and demultiplexer boards were designed to conform to the ITU-T Recommendations for SDH. Due to the developing nature of such standards, it has been necessary to monitor closely any changes. Several useful meetings have been held with representatives of the standards bodies; this has enabled the ASIC designs to conform to emergent SDH standards.

6 PUBLISHED PAPERS, PUBLIC DEMONSTRATIONS

In the course of the Project, at least thirty-four papers have been published. These include papers for journals, conferences, and presentations at

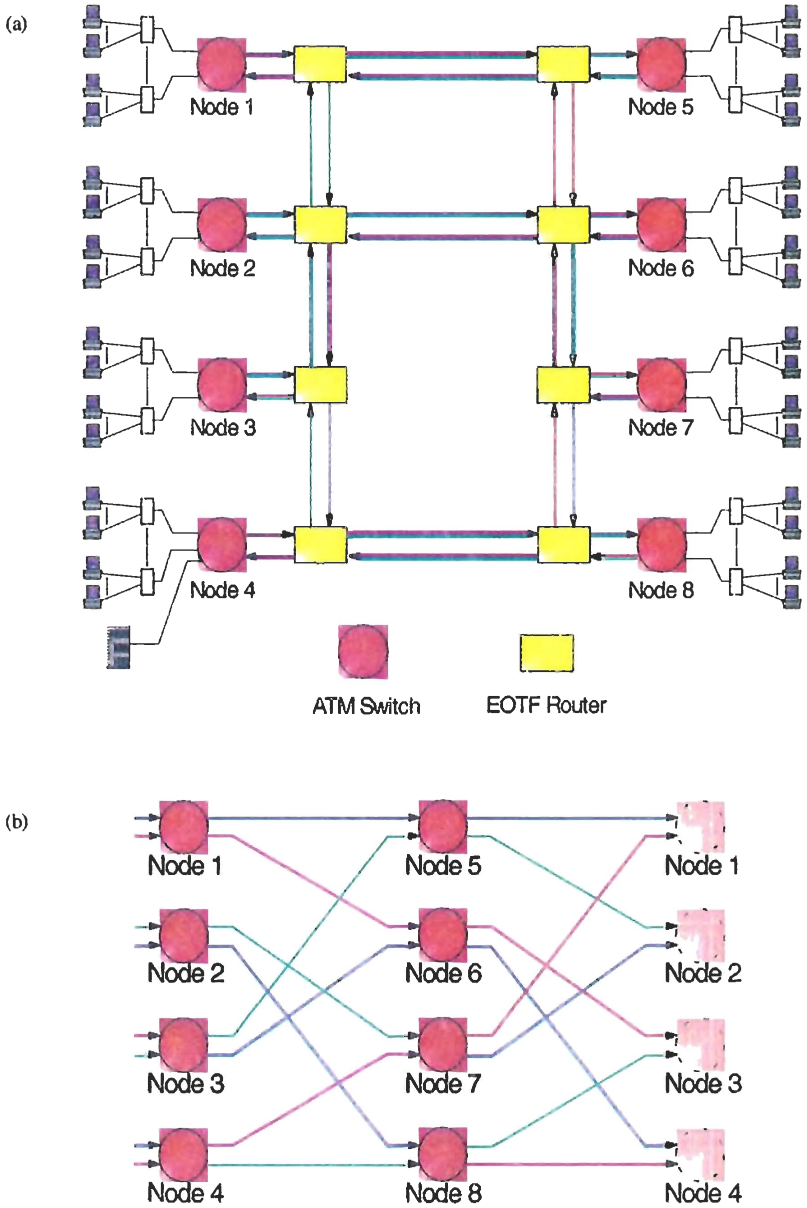

Fig.27 - (a) Equivalent physical ATM network with eight EOTF optical routeing elements and three reusable wavelengths
(b) Equivalent virtual shuffle net

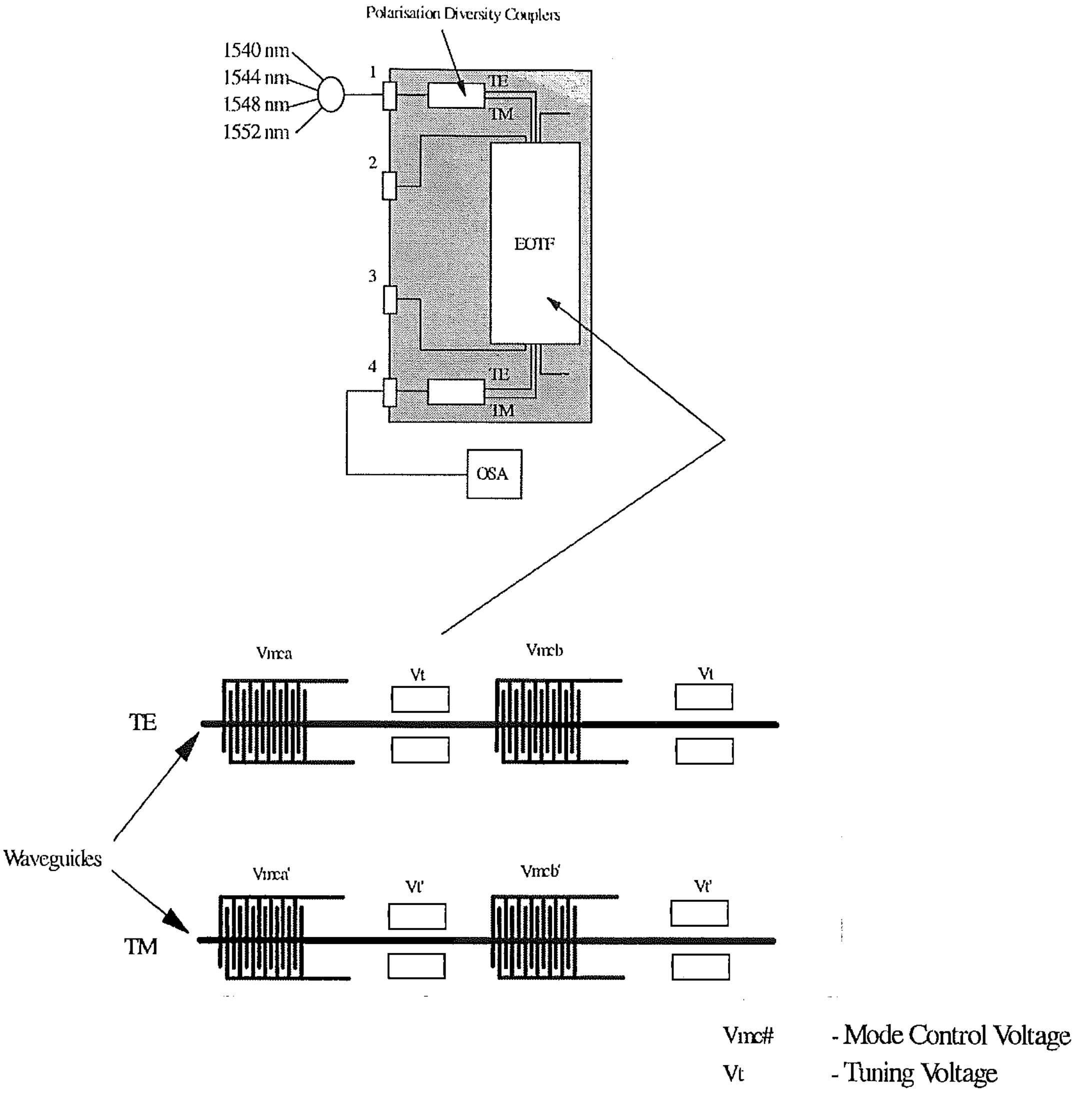

Fig. 28 - EOTF module and waveguide detail

RACE, Eurescom, EBU and other workshops.

Throughout the course of the Project, working equipment has been shown at many exhibitions, including three European Conferences on Optical Communications, the International Broadcasting Convention, and the International Television Symposium.

Two high-profile public demonstrations were offered to influential audiences during the Project; one in March 1995 when WTDM was shown to RAI Research Centre in Turin, and one in Oslo at the premises of Norwegian Broadcasting Corporation, (NRK), in September 1995.

7 COMMENTS FROM THE USER (NRK)

NRK, like most public broadcasters, has had to take into consideration existing installations when renewing the technology. New equipment has to communicate with old, and organisation structure is often adjusted to infrastructure and vice versa. This is a complex task, and it is not made easier by present fast developments in technology. In the following, we describe our existing facilities, and our approach to future planning.

Existing production facilities

Studios

NRK has four analogue studios. The production equipment is mainly based on the PAL format, but some of the graphical equipment uses digital signal formats internally. The newest equipment (e.g. caption generators) has digital inputs and outputs.

The News Studio (Studio 5) is mainly digital It is connected to the other production areas by lines carrying analogue PAL. The cost of the conversion equipment between PAL and 270 Mbit/s made up a large part of the budget. In addition to this extra cost, the equipment produces extra heat and takes up extra space in the racks.

Editing rooms

For historical reasons, most of NRK's videotape recorders were placed in a central area called the 'film and tape' area. This is also the area for telecine. The videotape recorders were, and still are to a certain extent, used for replay during the transmission of programmes from the studios as well as for editing. Most of the equipment placed in this area is analogue. NRK bought approximately 120 digital Betacam videotape recorders for the Olympic Games, and several of these are situated in this area. The videotape recorders have analogue as well as digital inputs and outputs and they can therefore be easily fitted into the existing installations.

The Programme Building

In 1994, The Programme Building with editing rooms for news and electronic film production was inaugurated. The equipment installed in this building is digital. The interfaces to the rest of NRK's production areas are however in analogue PAL format.

The central technical area

The central technical area is NRK's interface to the outer world. Lines between different areas can be set up from this area. All signals are PAL and are routed manually by setting up paths from patch panels.

The continuity suite

The continuity suite is analogue. No automation for continuity is used today.

Routeing

All signals are routed manually by setting up lines via patch panels. The main patch panels are situated in the CTA (Central Technical Area) and in the tape and film area. The lines are based on coaxial cable terminated in a central cross-connection panel. NRK have dedicated a separate floor, the 'Cable Floor' for this.

Plans for the future

Digitisation of equipment and routeing

NRK will, in the course of time, replace the remaining analogue equipment with digital. By the year 2000, we expect that all of our production facilities will be digital. During this period we will reach a point were it is better to route the signals digitally than to convert them into analogue PAL first.

There are several reasons why we would like to go digital. The low bandwidth of the coaxial cable will restrict us from routeing future high-resolution production formats like HDTV. More and more of the production equipment will probably be based on data equipment and data disks. Demands for faster than real-time transmission of signals are then expected to arise.

Another reason for moving to digital is to improve the technical quality of our signals and to be prepared for eventual production in the 16:9 picture aspect ratio.

New project group to evaluate infrastructure

NRK have just increased the program service by starting a new TV channel. For economic reasons, we would like to control parts of the continuity functions from automation programs. NRK will for the same reason evaluate the total infrastructure to see if it can be made more efficient. The results from this evaluation will probably influence the routeing requirements. NRK will look for a flexible and future-proof technology at a reasonable price, to allow for the fast development in technology as well as changes in organization structure.

A project group with several sub-groups will specify the needs, and are responsible for planning and installation of the new infrastructure. The sub-groups are looking at the following areas: continuity, studios, CTA and editing. The project group started its work in October 1995. The renewal of the infrastructure is planned to start in 1997/98.

Why a new group when NRK have already specified our needs for a future routeing system as part of the RACE 2001 project? There are several reasons for this. Routeing is only part of the infrastructure, but the choice of infrastructure will influence strongly the choice of routeing technology. The inauguration of the second TV channel clearly influences the needs for routeing, and the old specification will therefore have to be modified. Developments in new technology offer competition to RACE 2001 in the choice of routeing technologies. These will of course have to be evaluated.

We may find that we have to choose a solution based on several technologies, each of them optimal for different needs.

Experience gained from the work done in the RACE 2001 Project will of course be used in the new project group.

Optical technology

The length over which digital TV signals can be transmitted through coaxial cables is limited. Some manufacturers guarantee up to 200-300 m, but in practice the length is usually much shorter.

NRK finds that fibre installations have a number of advantages compared to coaxial cable:

- Optical fibres provide capacity for future expansions in bandwidth.
- Optical fibres are immune to hum and other types of electromagnetically created noise.
- Optical fibres allow for transmission of 270 Mbit/s signals over large distances without regeneration.
- Optical fibres take up less space, and are therefore easily fitted into existing cable conduits without removal of the coaxial cables.
- Optical fibres are cheaper than coaxial cables.

Since a new routeing system is estimated to have a lifetime of more than 20 years, we believe that installations between production areas should be based on optical fibres.

The RACE 2001 system is therefore still of great interest. The pilot installation shows that the system easily can be expanded from direct optical links to full WTDM. This is of particular interest since some of the components used in the project are in an early phase and therefore cannot be bought off-the-shelf. Lack of global standardisation (i.e. 270 Mbit/s mapping into SDH frames and WDM) will also reduce the amount of suppliers of the equipment needed. This influences price and maintenance costs, which are of major concern to us. There is however work going on to standardise the wavelengths to be used in WDM.

NRK spent some time before the end of 1995 in evaluating the RACE 2001 pilot installation. We are still a little bit concerned about using SDH for routeing of uncompressed 270 Mbit/s signals inside our premises. This is mainly because this technology seems to be somewhat more complex than needed, and there is no universally agreed mapping standard supporting it. We expect that studies and measurements on SDH will clarify whether our concerns are to be justified or not. Such studies will be of use to NRK no matter what the conclusion will be, because we expect to be offered this technology from the telecommunications organisations.

Uses of different optical technology will also be studied.

8 COMMENTS FROM THE INSTALLER (GEC-Marconi)

From the beginning of the WTDM programme, at the start of Project R1036, this implementation of WTDM has been directed at meeting the particular needs of broadcasters to distribute digitised television signals around a large television installation in a completely non-blocking way. When the R2001 system was originally proposed for the BBC Cardiff refurbishment the architecture development was still in its infancy, and the system proposed was not the most efficient in terms of component layout to ensure a low cost and affordable installation. Added to this was the requirement of BBC Cardiff for a distribution system handling almost exclusively analogue television signals. This type of installation requires many digital converters, in addition to the added synchronisation limitations, which made it impossible to achieve a sufficiently low installation cost for the proposed WTDM router. As a result of the experience gained through preparation of the proposal for BBC Cardiff it has been possible to identify more efficient means of configuring WTDM installations which can offer broadcasters advantages over the conventional alternatives of central switching routers.

Additionally, a technological change has been sweeping the broadcasting industry over the last three years, which has diverted attention away from High Definition Television (HDTV) and towards the universal acceptance of digital television standards for all aspects of picture generation, manipulation and transmission. This move has intensified the requirement for routeing systems which are capable of handling high data rate signals at 270Mb/s or even at 360Mb/s, which can be supported only by very short lengths of coaxial cable. Although this move has ensured that fibre-optic links are the technology of choice for digital television installations, the full potential capacity of fibres is not being realised on systems which use the fibres to replace existing coaxial links. This capacity can only be fully utilised by transmitting multiple wavelength channels simultaneously down each fibre, whilst using time division multiplexing (TDM) to take advantage of the speed of current electro-optical components.

Although WTDM has shown a route by which the full capacity of installed optical fibre can be realised, the implications on system cost can be considerable. WTDM routeing is expensive at current costs, particularly in comparison with the conventional switching alternative, but by careful system design and by assuming achievable cost reductions in certain key components it is possible to provide improved routeing capabilities for a comparable cost on a per channel basis.

There are also situations where limitations are set, for example by the number of available installed optical fibres, and then wavelength or time division multiplexing becomes the only option for increasing the capacity of a network, in which case the cost basis is changed in its favour. There are also situations in which, for example, capacity on a fibre is paid for on a per fibre basis, and the cost of leasing additional fibre is greater than the cost of installing additional WTDM equipment. For these reasons the cost analysis of installing a WTDM router is complicated, particularly if the target site is conscious of its future needs when the economic arguments will not be the same as those for the initial installed system.

9 COMMENTS FROM THE PRIME CONTRACTOR (BBC)

The original aim of the Project—to specify and install an optical broadband CPN in an operational environment—has been fully achieved. The components developed have put the Project at the forefront of technology.

A number of products developed in this Project have reached or are about to reach the market—a significant achievement in terms of the aims of RACE II. Work on WTDM applications has begun and ended on a solid foundation: the study of the needs of real users at Cardiff carried out in the first year of the Project has been well applied to the design of the pilot installation demonstrated in Oslo. Two high-profile demonstrations and many appearances at exhibitions have heightened the awareness of potential users of the benefits of optical routeing techniques.

All Partners have worked to accomplish the aims of the Project with flexibility and enthusiasm, and have shown patience and resourcefulness during some difficult reorganisation and restructuring. Their helpful and friendly approach has made possible the solid progress achieved, and throughout the lifetime of the Project all of the work has been carried out in a wonderful spirit of co-operation.